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FLIGHT EXPERIENCES AND TESTS ON TWO AIRPLANES WITH SUCTION SLOTS

By Stüper

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FLIGHT EXPERIENCES AND TESTS ON TWO AIRPLANES WITH SUCTION SLOTS*

By Stüper

Abstract:

In this report, the flight tests of two airplanes with boundary-layer control are reviewed. The results for take-off and flight test measurements are reported. During flights, the suction proved to be an effective means of obtaining high lifts.

Outline:

*"Flugerfahrungen und Messungen an zwei Absaugeflugzeugen." Zentrale für wissenschaftliches Berichtswesen der Luftfahrtforschung des Generalluftzeugmeisters (ZWB) Berlin-Adlershof, Forschungsbericht Nr. 1821, July 1, 1943.

I. INTRODUCTION

In his first report on boundary-layer theory in 1904 (reference 1), Professor Prandtl pointed out that suction applied to the boundary-layer is a means for preventing flow separation. He studied on a water channel, among other problems, the flow about a circular cylinder, figures 1 to 4. The effect of the suction can be very well recognized in the figures.

In 1923, Professors Betz and Ackeret suggested making use of suction for wings (D.R.P. Nr. 458428). Very high lifts are to be attained by prevention of separation. Ever since that time, suction has been a special field of research of the Aerodynamische Versuchsanstalt Göttingen (AVA) (references 1 to 40).

From 1925 to 1939, the problems were developed under the direction of O. Schrenk; after 1939, under the direction of B. Regenscheit. Among the collaborators, A. Wöckner must be mentioned in particular; he directed design and construction of the first airplane with suction slots (AF 1) and performed the first flights with it.

At first, suction was not used in industry since structurally simpler means for attainment of high lifts (slat, flap, Fowler-flap, etc.) were thought sufficient. Thus the AVA decided in 1932 to undertake itself the testing of suction in flight by developing, designing, and constructing an airplane with suction slots. Various reports on this first airplane with suction (AF 1) have been published (references 12, 13, 17, 19, 25).

Taking the experience with the AF 1 and more recent work in the wind tunnel as a basis, the AVA designed and constructed a second airplane with suction (AF 2) in 1939 and 1940.

Both airplanes were the result of close collaboration of separate work groups of the AVA. In the construction of the first airplane with suction, Ing. A. Wöckner directed design and manufacture; Dr. Ing. O. Schrenk was responsible for the flow-technical side of the problems. Strength calculations and statics had been taken over by Dr. W. Flügge. All three were temporarily advised by Dr. M. Kohler, H. B. Helmbold, and Dr. G. Messner. The work of modeling and designing for the second airplane with suction (AF 2) was directed by Ing. K. Grothey. Dipl.-Ing. W. Krüger solved the flow-technical problems. Dr. P. Jordan dealt with the problems of strength and statics.

The purpose of the present report is to present, after a short description of the two airplanes, the experience made with them in tests and surveys. Furthermore, complete results of the flight measurements are published for the first time. The problem of suction is treated only as far as it is connected with flight tests.

SYMBOLS

For the symbols used, deviations from the last standard DIN L 100 were permitted for the sake of maintaining the connection with earlier reports.

b (m)	wing span
t (m)	wing chord
d (m)	profile thickness
F (m^2)	wing area
G (kg)	flight weight
α (°)	angle of attack referred to the axis of fuselage

ϑ (°)	angle of incidence referred to the axis of fuselage
γ (°)	flight-path angle
β_{Kl} (°)	landing-flap deflection
$\beta_{H\ddot{o}}$ (°)	elevator deflection referred to the axis of fuselage
q (kg/m²)	dynamic pressure in flight
v (m/sec)	flight velocity
v_s (m/sec)	rate of climb
Q (m³/sec)	quantity of suction air per second
$c_Q = Q/Fv$	suction-quantity coefficient
$c_a = \frac{G \cos \gamma}{Fq}$	lift coefficient
$c_w = \frac{G \sin \gamma}{Fq}$	drag coefficient
c_m	pitching-moment coefficient referred to the center of gravity
λ	advance ratio of propeller
k_s	thrust coefficient
$\beta_{0.7R}$	blade angle of propeller at 70% radius
n	rpm of propeller
n_G	rpm of blower

II. THE FIRST AIRPLANE WITH BOUNDARY LAYER CONTROL (AF 1) OF THE AVA GÖTTINGEN

(a) General Considerations Concerning the Design

Various construction possibilities for suction exist; two of them are represented in figure 5. In the first case, suction is applied to a very thick profile. The profile drag of such an unusually thick wing may thus be reduced to the order of magnitude of a standard wing. The suction must be applied continuously during the flight. Simultaneously, a considerable lift increase for the thick profile is attained by the suction. Suction case 2 deals with a profile of standard thickness with flap. The suction is applied on the suction side at the junction between wing and flap. Thus the flow at the flap is made to adhere. For the wing with flap and suction slots, suction is, therefore, on the whole applied only in take-off and landing, in order to attain maximum lifts.

For designing a first airplane with boundary layer control by suction, the suction case 1 does not come into question since the airplane is under all circumstances required to remain normally airworthy at cessation of suction. Furthermore, the application of an excessively thick profile causes very great structural difficulties; the considerable variations of angle of attack between cruising and maximum lift conditions (around 40°) can hardly be brought about by merely changing the pitch of the airplane. The profile with flaps (suction case 2), on the other hand, reaches its maximum lift for smaller angles of attack, since the zero-lift direction is changed by the flap deflection. For these reasons, the AF 1 has wings with flaps. The following problems had to be clarified with the aid of that machine (25):

1. Possibility and effectiveness of suction during flight

2. Effect of suction on the flight characteristics

3. Effect of stopping of suction, particularly during slow flight

4. Comparison of flight-test and wind-tunnel data

(b) Description of Design

Figure 6 shows the three-view diagram of the first airplane with boundary layer control in its original design (1936). The machine is a semihigh wing cantilever monoplane of wood construction. The numerical data are compiled in a table on page 37. The wing, figure 7, has a trapezoidal plan form with a taper ratio of 0.57. The trailing edge can be deflected downward over the entire span; the flaps are divided in the middle. Since in this flap arrangement no room for the ailerons was left on the wing, they were installed underneath the wing. End plates were joined to the wing tips in order to remove the outgoing vortices as far as possible from the suction slot and the ailerons. Wind-tunnel measurements had shown that with this arrangement the suction quantity required for attainment of a certain lift may be smaller than when the end plates are lacking (reference 17). Later control measurements in the wind tunnel, however, showed only slight advantages due to the end plates.

Figure 8 represents the profile sections. The profile with flap was developed especially for the AF 1. The thickness decreases from 20 percent in the proximity of the fuselage to 17.6 percent at the wing tip. The hinge of the flap lies in the surface of the pressure side. One recognizes how the suction slot on the suction side originates at deflection of the flap. The suction equipment is installed in the fuselage between the seats of pilot and observer, figure 9. The blower is placed on a vertical axis between the two main panels, the position of which is determined by front and rear spar. It is driven by a 600 cm^3 DKW motor mounted in the observer's cockpit. A bevel gear drive with a reduction ratio of 1.5:1 serves for transmission. For the maximum blower rpm of 2100, the power output is about 18 hp. The air sucked in through the flap slot enters, according to the arrow marking, the space between front and rear spar through the perforated rear spar; thence it flows toward the fuselage center, then through the blower and then on the bottom of the fuselage out into the open. The apertures in the rear spar are of different magnitude; they are dimensioned according to wind-tunnel measurements so that the distribution of the quantity sucked in along the span takes place as uniformly as possible.

Since the airplane was to serve exclusively for testing of suction during flight, a utilization of the energy of the sucked-off air, for instance by blowing out at suitable points of the wing, was omitted. Besides, more energy would have to be supplied to the air for that purpose (reference 46). For the sake of simplicity in the construction of the AF 1, no attempt was made to cancel or reduce the drag increase connected with suction (reference 11) by expelling the jet of sucked air rearward in the flight direction.

Figures 10 to 13 show photographs of the airplane; figures 12 and 13 demonstrate the formation of the suction slot.

(c) Flight Characteristics

In evaluating the flight characteristics of the AF 1, it must be noted that that airplane is chiefly assigned to testing purposes. Thus the incorporation of special features, as for instance in case of an airplane destined for mass production, was uncalled for. Thus, allowance was made consciously of certain deficiencies already recognized in the design. There follows a compilation of the estimations of the pilots who had the opportunity of flying the AF 1 in its original design (Wöckner, Ballerstedt, Stüper) and after the reconstruction (Pretshner, Seeger, Wieters, Stüper).

In a description of the flight characteristics, a classification according to the axes suggests itself.

Lateral axis.- The longitudinal stability of the AF 1 is sufficient for all states of flight, with power off and on, with and without flap deflection, with and without suction. It is true, it becomes vanishingly small in a climb with full power, with full flap deflection without suction; yet controllability is always maintained. For the rearward position of the center of gravity of about 0.3 t (measured on the profile at a distance of 0.225 span from the symmetry plane), the effectiveness of the elevator is good and sufficient. The location of the center of gravity was not changed during the tests. The control force is small. All flight conditions may be flown without variation of the stabilizer trimming adjustment.

Extending the inner flaps results in tail heaviness which is reduced by additional extending of the outer flaps. With the setting in of suction, the airplane becomes slightly tail-heavy. The nose-heavy moments originating on the wing by flap deflection and suction are therefore almost compensated by the tail-heavy moments of the horizontal tail surfaces which stem, among other causes, from the increase of the downwash angle.

Vertical axis.- Directional stability exists. The effectiveness of the vertical tail surfaces in standard flight is good; however, for lift coefficients exceeding 2 it deteriorates considerably and becomes insufficient for maximum lift. Because of the propeller slipstream, straight flight at full power requires some rudder deflection; for $c_a = 4$ the rudder is fully deflected. For further decrease of dynamic pressure, the airplane can be flown in straight flight only by gliding flight ("Hängenlassen").

Longitudinal axis.- The aileron arrangement proved inadequate. In standard flight, the control forces were of almost unsurmountable magnitude. The effectiveness was exceedingly small. Rearward shifting of the aileron hinge line from 17 percent to 11 percent of the chord failed to produce essential improvement. Probably the mutual influence of wing and aileron reduces the aileron effectiveness; however, control with respect to the longitudinal axis was possibly due to the large rolling moments with sideslip and with yawing velocity when the rudder is deflected. In addition, the machine was very stable with respect to the longitudinal axis due to the dihedral. In this manner, even steep turns and eights could be performed exactly.

For stalling flight with flap deflection without and with suction, the control forces of the aileron became quite moderate (literally, "well-mannered"), and compared to standard airplanes in the region of high lifts the effectiveness was tolerable. As mentioned above, the rudder effectiveness decreases the more, the slower the flight; however, the coupling of the motions about longitudinal and vertical axis was maintained so that, for stalling flight, rotations about the vertical axis could be produced by aileron deflection.

Because of the defective aileron characteristics, the wing of the AF 1 was remodeled as described below.

Behavior in stalling.- Stalling of the airplane in straight flight was produced by slow pulling of the elevator, thus was in an almost unaccelerated condition. The aileron was kept in mean position, the rudder deflected as far as required for straight flight.

For stalling with power off and with a flap position 0°, the airplane oscillates about the longitudinal axis and then pitches down slightly without considerable rotations. With increasing flap deflection, the motions become noticeably smoother; with suction, the oscillation ceases. For calm weather conditions with $\beta_{Kl} = 45^{\circ}$ with suction, the elevator could be pulled through to maximum deflection while the airplane performs small oscillations of constant amplitude and frequency about the lateral axis (nictitating oscillations). If, however, aileron actuation was made necessary by slight gustiness, the machine pitched down.

With the power on and a flap position 0°, the oscillations about the longitudinal axis were more energetic. In case of further pulling, the airplane rolled off. With extended landing flaps, the oscillating ceases. In stalling, the machine rolls over to the left and assumes speed. With suction, the AF 1 rolls suddenly, with a very violent jerk, without previous warning to the pilot by separation phenomena or the like.

According to wind-tunnel investigations, it had been assumed that, for separation of the flow on one side of the wing, the suction would make the flow adhere again on this side, at the expense of the wing side with unseparated flow. If the latter then separates, the procedure perhaps might be repeated. Consequently an alternating rolling to the one and to the other side would appear. The phenomenon could not be observed on the AF 1. The machine always rolled to the left, assumed speed and could easily be leveled. Even for fixed control, it never showed spin tendency. For take-off or climb, these rolling characteristics are unimportant, in spite of the lack of a warning to the pilot, since the flight condition shortly before the rolling is far remote from the condition of optimum angle of climb or of maximum rate of climb. With the power on for $\beta_{Kl} = 45^{\circ}$ with suction, the airplane shows, shortly before rolling, sinking speeds of about 1 meter per second.

For several tests, the angles of yaw of the AF 1 were increased before the stall. For $\beta_{Kl} = 45^{\circ}$ the machine could be made to roll with the power on or off and with or without suction.

Sudden stop of suction.- This problem was investigated with particular care. With power off or on, the airplane with fixed elevator assumes, immediately after cessation of suction, larger pitch at first. Then the pitch decreases; the speed of rotation about the lateral axis after the stopping in the range of high lifts amounts to about 3° per second. Winging over or irregular rolling oscillations at stall never occurred for sudden cessation of suction, not even when the c_a-value before stopping the suction was so large as to be unattainable in flight without suction. The phenomenon gives the pilot the same feeling as when the landing flaps on an airplane with flaps are retracted vary rapidly (for instance, He 70).

During the flight tests on the AF 1, in stalling flight the suction was stopped unintentionally more than once. Alarming conditions never resulted.

Influence of weather.- In turbulent atmospheric conditions, flying of the machine was not simple, due to the unfavorable aileron characteristics. Straight flight could then be performed only with great difficulty. In stalling flight, the influence of gusts is very large because of low wing loading. For suction, no deterioration of the behavior compared to the condition without suction resulted due to gustiness. Rain did not cause any particular difficulties.

(d) Reconstruction of the Airplane

The aileron arrangement was altered before the beginning of the flight measurements. According to a suggestion by Gropler (Junkers Flugzeugwerke Dessau), part of the outer landing flap was developed as aileron. Figure 14 shows a profile section in the region of the outer landing flap; the new arrangement is recognizable. Furthermore, the end plates were omitted; the wing obtained a curved tip strip, figure 15. The rudder chord was increased by 150 mm. Figure 16 shows the new complete plan-view of the airplane, figure 17, a photographic view.

The new aileron arrangement proved good. Due to the yawing moments causes by an aileron deflection, however, proper flying was possible only by simultaneous use of the rudder.

For flap position 0°, an aileron deflection causes, in high speed as well as in stalling flight, a pronounced rotation of the airplane about the vertical axis against the curve direction due to the bank. This rotation starts simultaneously with the favorable rolling motion and produces very large angles of sideslip, thereby almost neutralizing the bank. For fixed rudder and aileron deflection, the airplane thus continues its rectilinear flight with considerable angles of sideslip. For incidence of the landing flaps and ailerons, this behavior is no longer so pronounced. Here the airplane again rotates initially, for fixed rudder and aileron actuation, in the inverse direction about the vertical axis; it reverses to the right direction of rotation, however, after a certain rotation which increases with mounting c_a and growing rudder deflection.

The rolling effect of the aileron becomes almost vanishingly small for large c_a values ($\beta_{Kl} = 45^\circ$) without suction. Full aileron deflections cause only very slight rotations in roll although the flow at the aileron itself is perfectly unseparated. If suction is applied in this condition, the rolling effect very much improves for equal aileron deflection and dynamic pressure. This phenomenom may be easily explained. As was shown by investigations, the flow adheres, without suction, to the aileron; it is separated, however, at the part of the flap in front of the aileron. The rolling moment caused by an aileron deflection consists of two parts. One stems from the forces attacking at the aileron itself, the other from the alteration of the air forces on the entire wing caused by the aileron deflection (camber variation). In the case without suction mentioned above, the aileron lies in the wake of the flow separated from the flap. Retroaction of the aileron deflection on the wing flow is thereby largely prevented. There remain chiefly the forces on the aileron itself; however, they are small due to the wake. Thus the total effect is only very slight. With application of suction, the flow at the flap is made to adhere; the aileron effect becomes good.

The rolling motion in the high-lift range with suction is disturbed very considerably by rotation about the vertical axis. Aileron deflection produces larger rotations about the vertical axis than banks. The rudder is completely inadequate for these yawing motions in case of an aileron deflection. Even for slight gustiness, the airplane in the range of $c_a = 4$ can be flown at full power straight only with difficulty because every bank compensated by aileron deflection immediately causes a strong rotation about the vertical axis.

(e) Flight Performance Measurements

Tuft investigations.- Tuft investigations were performed in order to obtain as simply and clearly as possible a qualitative understanding of the effect of suction. In figure 18, the tufts are visible on the wings. The behavior of these tufts was recorded in flight by means of the camera mounted on the fuselage. Without suction the flap is separated from $\beta_{Kl} = 10^\circ$ onward, whereas with full suction ($n_G = 2100$ rpm) the flow still adheres even for a flap angle of 50°. Suction can accomplish even more. In the film, one could observe how, for $\beta_{Kl} = 45^\circ$, the completely separated flow is made to adhere by turning on of the suction.

If, in the range of maximum lift, the rpm of the suction blower is slowly reduced, separation of the flow at the landing flaps starts between 1900 and 1800 rpm. It could be observed that the separation phenomenon by no means occurs suddenly as for instance the sudden change of a neutrally stable condition. Rather, separation is a continuous phenomenon, the intermediate states of which may be maintained any length of time. To what extent the flow still adheres depends chiefly on the suction quantity coefficient.

Take-off measurements.- The well-known photographic method (reference 12) was applied for the take-off measurements with the AF 1 in its original design. After the reconstruction, the airplane was furnished with a device for measuring the speed with the aid of a "log;" figure 19 shows the installation of the "log" far ahead of the wing. The measuring method by "log" proved excellent, particularly for exact determination of the low speeds for take-off and high lift. Thus this method was widely used in the measurement of the two suction airplanes. In order to avoid wind influence, all take-offs were performed only in perfectly still air. Figure 20 shows the magnitude of the rolling distance on the ground as a function of the flap deflection, whereas figure 21 indicates the value of the lift coefficient at the instant of the lifting off the ground. Figure 22 represents the variation of the coefficient c_Q; the rpm of the blower was for all take-offs with suction about 2150. One has fixed the moment when the wheels of the landing gear leave the ground as the moment of lifting of the airplane. It has to be considered that, due to the very long spring range of the landing gear, the wheels, before the lifting, run on the ground due to their own weight while the machine is already flying. Consideration of this influence would somewhat reduce the rolling distance, figure 20, and slightly increase lift and quantity coefficient, (figures 21 and 22), (reference 19).

The take-off distance, that is, the distance between standstill and attainment of a flight altitude of 20 meters, is, in general, of greater importance for judging the take-off performances of an airplane than the rolling distance. For the AF 1 there results, without suction, the influence of the landing-flap deflection (figure 23), known from airplanes with flaps. Only a small deflection ($\beta_{Kl} = 9^{\circ}$) is advantageous, and even then the gain in take-off distance is exceedingly small. For full suction, a slight reduction of the take-off distance up to the maximum landing-flap deflection may be observed. The difference compared to take-offs without suction is insignificant. Without suction, the shortest take-off distance is 450 meters; with suction, 395 meters; thus the shortening amounts to 55 meters (12 percent). An equal gain may be obtained by a head wind of only about 2 meters per second. If, for the take-offs without suction, the suction power of 18 hp would be additionally supplied to the propeller (which perhaps ought to be done for a correct comparison), the application of suction brings hardly any advantage for the take-off distance of the AF 1.

However, suction at take-off remains valuable for airplanes where a short rolling distance or particularly small lifting-off speed are of importance, for instance, hydroplanes. Here, the gain by suction is very considerable; the lift coefficient for lifting-off of the AF 1 is almost doubled, and the rolling distance reduced by one-half.

A further advantage of the application of suction was found in the small values of pitch for which high lift values are attained. This will be discussed in more detail below in the comparison of the two suction planes.

The take-off characteristics of the AF 1 were agreeable. Not the slightest tendency towards veering off was present. Immediately after applying full power, one could get the tail up. The transition into the climb after leaving the ground occured without large rotations about the lateral axis.

The explanation for the relatively small take-off ratings of the AF 1 (large take-off distance and low climbing speed) lies in the high power loading. The maximum power of the aircraft engine of 215 hp for 2400 rpm could not be applied, since a critical range of 2150 to 2300 rpm was in too close proximity. Thus the propeller was adjusted so that for full power a maximum rpm of 2100 was attained at about v = 70 km/h. The power output is only 150 hp. For higher speeds, a short-time increase of the motor rpm up to n = 2400 rpm with corresponding power increase was admitted, particularly for the investigation for full power.

Measurements with suction (n_G = 2100 rpm) and without suction.- The measurements described in this section were made by my friend, Walter Pretschner, in Dessau after the reconstruction of the AF 1 during the years 1938 and 1939. He lectured about a part of his work at a meeting of the Lilienthal-Gesellschaft in Dessau on December 13, 1938; he never published it[1]. I presume to enter into his ideas in representing here the results of his measurements.

The flight-performance measurements in this report are represented uniformly in the following manner. The values, measured in flight of rate of climb, pitch, elevator deflection, and suction quantity are represented as functions of the flight dynamic pressure. The curve, determined in every case by the position of the test points, served as basis for the calculation of the further values of path inclination, angle of attack, lift and drag coefficient. In this manner, I have evaluated anew Pretschner's measuring data which were left to me.

Part of the measurements were made in an intermediate state of construction of the AF 1 in order to determine the influence of the wing end plates; the AF 1 then had already the new aileron arrangement but still possessed the end plates, figures 18 and 19. The comparison

[1]Flight captain Dipl-Ing. Walter Pretschner, Chief pilot of the Junkers-Flugzeugwerke Dessau, died a flyer's death in a high-altitude flight on January 24, 1940.

with measurements without end plates, figure 17, did not show any difference within measuring accuracy.

Pretschner drew my attention to the fact that he had to perform, for reasons of time limits, part of his test flights under very unsuitable weather conditions. For the sake of better controllability, he deflected for the large landing-flap deflection ($\beta_{Kl} = 45^{\circ}$), the inner flaps by 45°, the outer flaps by 40°. This arrangement was maintained in my flights described in the next section, in order to keep the continuity. Pretschner's measured results were very well reproducible in repetition except for the sinking speed with power off without suction. Here, the four measuring values between $q = 35$ kg/m^2 to 54 kg/m^2 given by Pretschner seem to be falsified by upwash. The course of the curve I measured is plotted in figure 24; compare figure 34 also, $n_G = 0$.

The measuring flights were made at altitudes of 400 to 800 meters. During the measurements, the suction motor was operating at full power; the blower had an rpm $n_G = 2100$ which for maximum lifts increased to about $n_G = 2200$. The suction quantity for the high-lift range was about 7.5 m^3/s. Figure 24 shows test values for rate of climb, figure 25 and 26 those for the pitch, with power off and on as a function of the dynamic pressure in flight. The small rate of climb results, as mentioned before, as a consequence of the high power loading. The relatively large increase of the rate of climb for full power and $\beta_{Kl} = 45^{\circ}$ by turning on of the suction is caused by the drag reduction. The latter results due to the disappearance of the wake for nonseparated flap flow. The pitch for maximum lift with suction is of almost the same magnitude as for the considerably smaller maximum lifts without suction and without flap deflection.

The plotting of the lift against the angle of attack, figure 27, shows the large increase of lift by suction. The lift at full power also includes the influence of the propeller. It is essentially a question of the slipstream influence, the increase of the dynamic pressure at the center part of the wing. For the small angles of attack, the share of the propeller thrust responsible for the lift is only very slight. On the other hand, the propeller causes a lift decrease for the measurements with power off, since the flow at the center part of the wing is somewhat disturbed. Figure 28 gives the polars of the airplane for the various operating conditions. The coefficient c_w contains the propeller thrust.

In all test flights, the deflection of the elevator was measured, figures 29 and 30. The angles are referred to the fuselage axis. The horizontal stabilizer was fixed at 0° position. A stabilizer adjustment to 6° corresponded to an elevator deflection of 8°, thus one had $\dfrac{\partial\beta_{stab}}{\partial\beta_{H\ddot{o}}} = 0.75$. The aft position of the center of gravity was 0.3 t, measured on the profile at a distance of 0.225 b from the symmetry plane. The variation of the elevator deflection leads to the assumption that with the power off with suction and a position of the center of gravity further forward, the effectiveness of the elevator is not sufficient for obtaining a three-point landing.

From the value $\frac{d\beta_{H\delta}}{dc_a}$ which can be taken from figure 31, certain conclusions may be drawn as to the static longitudinal stability:

$$\frac{d\beta_{H\delta}}{dc_a} = \frac{dc_m}{dc_a} \frac{1}{dc_m/d\beta_{H\delta}}$$

Therein $\frac{dc_m}{dc_a}$ is a measure for the static stability and $\frac{dc_m}{d\beta_{H\delta}}$ a measure for the elevator efficiency. If one wants to estimate the longitudinal stability from $\frac{d\beta_{H\delta}}{dc_a}$ one assumes $\frac{dc_m}{d\beta_{H\delta}}$ to be constant. For $\beta_{Kl} = 45^\circ$ and full power without suction, the longitudinal stability becomes, with increasing lift, vanishingly small; this statement has been made before, together with the estimation of the flight characteristics. With suction, however, longitudinal stability exists for the entire range. It may even be assumed that the elevator effectiveness is smaller for flight with suction. By the adhering flow, the propeller slipstream is deflected downward and no longer impinges on the elevator.

Influence of the suction quantity.- In order to include the influence of the suction quantity on the flight performances and characteristics of the AF 1, the rpm of the suction blower was reduced by steps from $n_G = 2100$ to $n_G = 1700$ in a series of test flights with $\beta_{Kl} = 45^\circ$ and power off. Great difficulties had to be surmounted in determining the suction quantity in each case. The measurement of the suction quantity at standstill had shown the velocity distribution of the outflowing air to be considerably nonuniform and, moreover, variable with time. Finally, one succeeded, by measuring the flow velocity of the air in the wing near the fuselage, in obtaining sufficiently exact values of the suction quantity in flight also, figure 32. The measuring values varied by about ±4 percent; for the sake of greater clearness, the test points have, therefore, not been plotted. The quantity depends not only on the blower rpm but also on the flight velocity. The sudden drop in capacity is a consequence of the partial flow separation at the blades of the blower wheel.

All measuring flights were performed at about 1000 meters altitude ($\rho = 0.113 \text{kg-sec}^2/\text{m}^4$). The aircraft engine was throttled to power off. Figure 33 shows its rpm for the different dynamic pressures. In general, the rpm corresponding to a certain dynamic pressure is satisfactorily constant. For comparison, the curve for the operating condition where the propeller neither brakes nor pulls (zero thrust) has been plotted.

Figure 34 gives the measurements of the rate of climb, figure 35 those of the pitch. The large difference of ϑ between $n_G = 1700$ rpm and $n_G = 0$, although the flow at the landing flap had been fully separated for $n_G = 1700$ rpm, is surprising. This difference becomes particularly clear if the lift coefficients are plotted against the angle of attack, figure 36. With decreasing suction quantity, the lift also is reduced for the same angle of attack. The quantity for $n_G = 1700$ rpm is still sufficient to cause a considerable lift increase. The sudden drop in suction quantity (figure 32) which should be represented in these curves as corresponding lift decrease does not become manifest because the determination of the angle of attack is not sufficiently exact. The sinking speed enters into the numerical determination of the angle of attack which is, of course, for flight measurements always subjected to certain variations. Figure 37 shows the lift coefficient as a function of the quantity coefficient. The greater slope of the curves is caused by the more and more adhering wing flow.

The elevator deflection of the AF 1 for varying suction quantity are represented in figure 38. Here also the great influence of the suction can already be recognized for $n_G = 1700$ rpm, compared to the condition without suction. As figure 39 shows, the longitudinal stability remains almost unchanged for varying suction quantity.

<u>Summary</u>.- The experiences and knowledge obtained through tests on the AF 1 have shown unequivocally that suction is an exceedingly effective means for obtaining high lifts, also in its practical application in flight. By the use of suction, lift coefficients could be reached in flight which had so far not even approximately been attained with a rigid-wing airplane. It is by no means overlooked that many more problems still remain to be solved in connection with application of suction in flight. In order to further work and research in this direction, too, the AVA decided to develop a second airplane using suction.

III. THE SECOND AIRPLANE WITH BOUNDARY-LAYER CONTROL (AF 2) OF THE AVA GÖTTINGEN

(a) Description of the Design

The following desired features and requirements formed the basis for the design of the AF 2:

1. Reduction of the profile thickness to 0.18 t

2. Application and testing of two-slot suction

3. Providing for the possibility of exchanging the wing for another of still smaller profile thickness

4. Propulsion of the suction blower from the aircraft engine

The suction-flap profiles are very sensitive in their effect with respect to a reduction of the profile thickness (references 18 and 25). At the time of the designing, little was known about the influence of the profile thickness on the effectiveness of the wings with suction flaps. Thus, a profile only a little thinner than the AF 1, namely, the profile 6218, was selected at that time. The detailed investigations of B. Regenscheit had, however, demonstrated the advantages of a two-slot suction, especially its importance for the nonseparated quantity (reference 18). The group of the AVA for boundary-layer influencing suggested, therefore, construction of a wing with a flap with two-slot suction. Figure 40 shows two profile sections of the AF 2. The formation of the double slot for deflection of the landing flap may be well seen in the drawing. By means of a system of moving parts, a kidney-shaped intermediate part between wing and flap is moved in such a manner when the flap is extended that, on the suction side at the beginning of the break, a narrow suction slot and, further down in the curvature, a wide one originate.

The arrangement of the ailerons as parts of the landing flap (Gropler aileron) was maintained. The wing had approximately elliptic contour, figure 41. Since twist was lacking, the relatively strong taper of the wing led one to expect the airplane to have a tendency toward rolling at stall. However, the elliptic form was maintained because one wanted to draw conclusions from the flight tests to the profile characteristics. For that reason the c_a distribution was to be as constant as possible. Furthermore, one wanted to study the influence of suction, especially of the distribution of the suction quantity over the span, on the rolling behavior.

Realization of the third requirement led to designing the airplane as a strut-braced high-wing monoplane. Thus the static difficulties were best eliminated for later use of thinner wing sections. In order to simplify design and construction, fuselage and vertical and horizontal tail surfaces were taken over without change from the Fieseler-Storch (Fi 156), figure 42. In the table on page 37 the numerical data are compiled.

The single-stage blower installed in the fuselage is driven by the aircraft engine over a series of shafts, figure 43. The aircraft engine of the type Argus As 10 H has at the rear end a connection permitting up to 75 hp to be used out of the total power of 270 hp.

Directly in front of the blower lies a two-speed gear. At first speed, the rotor obtains its standard rpm, $n_G = 3000$ for a motor rpm of $n = 2100$; this corresponds to the operating condition at full power, as it exists for take-off and climb. At second speed, $n_G = 3000$ rpm is reached for a motor rpm of $n = 1050$; this is the operating condition for motor almost idling in gliding and landing. The sucked-off air comes out into the open at the rear part of the fuselage through lateral apertures. Figures 44 and 47 show photographs of the airplane.

(b) Flight Experiences

Lateral axis.- The AF 2 possessed good longitudinal stability for all operating conditions, with power off and on, with and without suction, with and without landing-flap deflection. The elevator effectiveness was very good, the control forces were normal. All flights were made using a single seat with a rear position of the center of gravity of 0.35 t, measured on the profile at the distance 0.225 b from the symmetry plane. The horizontal stabilizer was for all test flights rigidly fixed at 0°. Considerable reserves in control surface deflection always existed in the up direction. Thus a three-point landing could be assumed as possible also for a position of the center of gravity further forward. When the landing flaps were extended, the machine became tail-heavy. The setting-in of suction slightly increased the tail-heaviness. Thus here, too, a small over-compensation of the nose-heavy wing moments by tail-heavy moments of the horizontal tail surfaces existed.

Vertical axis.- The rudder effect was good for all dynamic pressures. For flight in maximum-lift range, straight flight was also always possible.

Longitudinal axis.- The effectiveness of the ailerons in standard flight was sufficient; however, for increasing flap deflection and decreasing dynamic pressure, it was reduced more and more until it occasionally almost disappeared for the high lifts. Tuft photographs showed that the flow at the aileron was unseparated but was separated at the part of the flap extending in front of it. In contrast, the aileron effect was satisfactory for the high lifts where the suction kept the flap from separating.

Behavior of the AF 2 in stalling.- For stalling with flap position 0°, the AF 2 showed perfectly normal behavior. With power off, no rolling occurred, whereas at full power, the machine rolled quite harmlessly just as was found from other airplanes. With the flaps deflected, the rolling behavior at stall became more pronounced and occurred for the large landing-flap deflection even with power off. As the scheme of the flap control in figure 48 shows, inner and outer landing flaps were extended simultaneously by a single hand crank. The ratio of the deflection of the inner and outer flaps might have been varied by changing the lever K4a in the represented manner. For the originally used arrangement I, the outer flap with the aileron moved almost linearly from 0° to 33° when the inner flap was extended from 0° to 48°. Due to the relatively high incidence of the outer part of the wing, the airplane rolled at stall because there the separation started.

In the arrangement II, the outer flaps attained only 20° in case of full deflection of the inner flaps. The rolling behavior at stall had become noticeably less pronounced and less harmful; altogether, rolling at stall occurred only from $\beta_{Kl} \approx 33°$ onward; however, this arrangement of the flap deflections is disadvantageous for the suction. Since maximum extension of the outer flaps was 20°, the two suction slots (cf. fig. 40) were very narrow. Thus it would have been difficult to suck off an air quantity corresponding to the inner wing in these locations.

For this reason, arrangement III was applied. Therein, the connection between the deflections of the two flaps was no longer linear. At the beginning of the extension, the outer flap lagged behind the inner; toward the end its deflection increased more rapidly. For $\beta_{Kl}(\text{inside}) = 48°$, on the outside, 33° were attained. Thus the full suction cross section was at disposal. It was provided that flap angles exceeding 35° were used only with suction.

The suction first made the rolling become more pronounced. A measurement of the pressure distribution in the wing along the span showed that the quantity of suction air decreased very strongly from fuselage toward wing tip. This fact immediately explains the increase in tendency toward rolling for continuous suction. By suitably selected reduction of the apertures in the rear span, the distribution of the suction power along the span was varied. This tiresome work was performed gratifyingly by W. Krüger of the Boundary-Laryer Research Group of the Wind Tunnel Institute. In the laboratory he connected a wing to a blower, sucked the air off, and measured the distribution of the suction quantity along the span. Figure 49 represents the result of his labors. The quantity distribution, originally decreasing very strongly, is changed by the additional throttling so that the suction in the tapered wing part is slightly greater than on the inside.

For power on, with suction, the rolling could not be eliminated. Tuft investigations showed that suction with n_G = 3000 rpm, for β_{Kl} = 35° and β_{Kl} = 48°, was not sufficient to make the flow on the flap adhere. Thus, in this case also, no essential improvement of rolling behavior could be expected from the suction. In contrast to the AF 1, the rolling of the AF 2 occurred in immediate proximity of the condition for optimum climbing angle and close to maximum climbing speed. This bad flight property considerably reduced, for full power, the attainment of optimum flight performances (high lift), in addition to the limit established by the insufficient suction quantity.

For power off and suction with $n_G = 4200$ rpm and $\beta_{Kl} = 48^{\circ}$, alternating rolling to one and to the other side occurred, as expected according to wind-tunnel investigations. For slow stall, the airplane first rolled by about 10° to 15° toward the right, then jerkily to the left up to about 70° bank; then followed a very rapid veering to the right up to about 160° bank. Thus the airplane was almost in upside-down position and was restored to normal position by a half loop downward. Films of tufts showed that the flow first separated near the fuselage, starting at the rear part of the right wing. Then it was here made to adhere again by the suction while the flow on the left wing separated. Then the suction restored here, too, relatively sound flow conditions while simultaneously the entire right wing was disturbed. It must be noted that the separation never started at the wing tip as is usually characteristic for the rolling at stall of an airplane. The alternating separation and subsequent rolling motion is to be regarded as a result of suction.

Sudden stop of suction.- The AF 2 also showed perfectly harmless behavior in case of sudden stop of suction. The airplane assumed a smaller pitch and resumed its speed corresponding to the new condition. The transition from one condition to the other took place very gently and without any rotation about vertical or longitudinal axis.

(c) Flight Performance Measurements

Tuft investigation.- Part of the voluminous tuft investigations on the AF 2 has already been described. The most important experience was the fact that the suction quantity for $n_G = 3000$ rpm was not sufficient to make the flow adhere in case of $\beta_{Kl} = 35^{\circ}$ and $\beta_{Kl} = 48^{\circ}$. The determination of the suction quantity at standstill for $\beta_{Kl} = 48^{\circ}$ and $n_G = 3000$ rpm showed that instead of the hoped-for 9 to 10 m^3/s only about 7 m^3/s were sucked off. The very uneven velocity distribution of the flow toward the blower, the narrowness of the suction slots caused by the two-slot suction, the deflection of the air flow, and the drags at the inside part of the wing and at the exit apertures made estimation and incorporation for the design very difficult and inaccurate. For full power, an augmentation of the quantity by increase of the blower rpm was possible only by an alteration of the gear ratio between aircraft engine and blower. For the time being, this incisive change was not made, especially since the measurements showed that smaller suction quantities also cause considerable effects. In case of power off, the blower rpm could be readily increased up to the power limit of the coupling. Rpm of $n_G = 4200$ was reached. With this suction power, the flow on wing and flaps was made to adhere for $\beta_{Kl} = 35^{\circ}$. For $\beta_{Kl} = 48^{\circ}$, however, the flow at the flaps adheres only up to about 80 percent. Thus a further increase in suction quantity would lead to a further flow improvement in this part.

The take-off conditions for the AF 2 were somewhat more favorable. Here the flow at the flaps adhered for $n_G = 3000$ rpm and $\beta_{Kl} = 48^\circ$, too, until the instant of lifting off the ground. A smaller suction quantity is sufficient to keep an unseparated flow from separating than is required to make a separated flow adhere once more (reference 18). Furthermore, one has, for the rolling during take-off, very high c_Q values whereas the suction coefficients in flight before the decrease in speed are small, due to suction effect.

Take-off measurements.- For the take-off measurements with the AF 2, the propeller was adjusted so that the maximum rpm of the aircraft engine n = 2100 was reached at the instant of lifting off the ground with full power. With suction, the blower then had $n_G = 3000$ rpm. Eighty-eight take-offs at a wing loading of 55 kg/m^2 were measured. The mean values of the measurements are given below. The rolling distance, figure 50, was considerably shortened by the suction. It had to be noted that the suction power of about 45 hp is furnished by the engine. The lift coefficient at the instant of lifting off the ground also increased strongly, figure 51.

For flap deflections exceeding 40°, sudden rolling occurred several times after the lifting off the ground. The occasionally very critical positions could be controlled without damage to the airplane; however, further confirmation of the location of the test points by frequent repetition was omitted. For this reason the course of the curves in this region is given as a dashed line. Figure 52 represents the quantity coefficient at the instant of lifting off the ground.

The plotting of the take-off distance (from standstill to 20 m altitude) in figure 53 shows that for the AF 2 also not much was gained by application of suction. It is true, one has to consider that for the landing-flap deflections exceeding about 30° the flow at the flaps separates shortly after the lifting-off.

Flight measurements without suction.- The measurements were performed for the operating conditions, full power and glide. For the gliding investigations, the blades of the propeller always were adjusted so that the thrust disappeared. Figure 54 represents the advance ratio of the propeller for zero thrust. The rpm of the aircraft engine was n = 1050; this corresponds for suction blower turned on at high speed to a blower rpm $n_G = 3000$. With the aid of figure 54, one may determine for each flight speed the propeller blade angle for which zero thrust was attained. By means of the pitch-setting mechanism it was adjusted for every test point. For the measurements at full power, the propeller always was adjusted so that n was 2100 rpm.

In order to include the influence of the flap deflection, the measurements were performed for the deflection angles 0°, 20°, 35°, and 48°. The given degrees always refer to the angle of the inner landing flap. The corresponding angle of the outer flap with aileron can be taken from figure 48. All flights took place at about 1000 meters altitude so that ρ was 0.113 kg s^2/m^4. Measurements were made in perfectly still air only. Nevertheless, dispersions (fig. 55) had to be accepted in determining the rate of climb. Extending of the landing flap caused a decrease in rate of climb due to the drag increase. Between $\beta_{Kl} = 35^\circ$ and 48°, this difference was particularly large. Figures 56 and 57 show the pitch of the AF 2 without suction for zero thrust and full power. By flap deflection, the zero-lift direction of the wing was altered and the pitch for unchanged values of dynamic pressure was reduced. The pitch could be determined very exactly, as can be seen from the small dispersion of the test points. A solid circle in the drawings signifies that the value was measured repeatedly.

The plotting of the lift coefficient against the angle of attack, figure 58, shows the known lift increase by the propeller. The maximum value of the lift at zero thrust corresponds approximately to the values known from airplanes with flaps, whereas the value for full power is smaller than values known from airplanes with full power and flaps. The wing would probably here also produce a higher value if the limit were not already reached due to the rolling at stall.

In this particúlar measurement, the connection between stabilizer and elevator deflection was determined, figure 59. Hence resulted $\frac{\partial \beta_{stab}}{\partial \beta_{H\delta}} = 0.75$. The same ratio was found for $\beta_{Kl} = 48^\circ$ with and without suction. For all other test flights the horizontal stabilizer was always fixed at 0°. Figure 60 gives the values of the elevator deflection of the AF 2 for zero thrust, figure 61 for full power. Extending of the landing flaps produced tail-heaviness which was compensated by adequate pushing of the elevator. The variation of the elevator deflection corresponds approximately to the variation of the landing-flap angle.

From figure 62 which shows the lift coefficient as a function of the elevator deflection, one can see that, for zero thrust, static longitudinal stability existed to a rather large extent; it was hardly dependent on the landing-flap angle; however, for full power, the longitudinal stability decreased with increasing flap deflection. The deflection of the curve for full power, $\beta_{Kl} = 48^\circ$ and high c_a values stems probably from a loss in elevator efficiency caused by the small dynamic pressures, the large downwash angles, and the wide wake region. Perhaps shiftings of the center of pressure on the wing were responsible for it.

Flight measurements with suction, n_G = 3000 rpm.- For all measurements described in this section, the suction blower had an rpm n_G = 3000. The tuft investigations had shown that the flow at the landing flaps which had separated without suction for a flap deflection of 20° adhered due to setting-in of suction. This is not the case for β_{Kl} = 35° and 48°; however, yet another difference in the tuft behavior can be observed for these two flap angles; for β_{Kl} = 48°, the flow was much more disturbed than for β_{Kl} = 35°. This difference is noticeable also in the rate of climb, figure 63. The drop in rate of climb for the transition from β_{Kl} = 35° to β_{Kl} = 48° is larger than might be expected from the jump between β_{Kl} = 20° and β_{Kl} = 35°. Figures 64 and 65 represent the pitch of the AF 2 for zero thrust and full power. The lift, figure 66, shows for suction, too, the well-known increase due to propeller influence. With the small quantity coefficient present taken into consideration, the maximum lift for the large landing-flap deflections fully agrees with expectations. Higher c_a values were readily attainable by increase of the suction quantity as shown below. The performances at full power were somewhat less favorable due to the rolling behavior.

The suction quantity for the AF 2 was determined by measurements of the air speed at four places in the ducting to the blower. This method proved very exact. The reproducibility of the test values was surprisingly high as can be seen from the small dispersion of the test points, figures 67 and 68. For zero thrust as well as full power, the suction quantity was, for the same dynamic pressure in flight, somewhat larger for β_{Kl} = 35° than for β_{Kl} = 48°. In figure 69, the curves for constant suction quantities are plotted. It is noteworthy that, for zero thrust and full power, the suction quantity of the AF 2 was almost independent of the dynamic pressure. One may draw the conclusion that the flow drags within the airplane were so large that the pressure variations at the suction slot caused by the different flight velocities had no longer any noticeable influence on the suction quantity. The quantity sucked off per second was for β_{Kl} = 20° about 5.5 m^3 and for β_{Kl} = 35° and 48° about 6.5 m^3; for zero thrust, it was somewhat larger than for full power.

The magnitude of the elevator deflections of the AF 2 with suction is shown in figure 70 for zero thrust, in figure 71 for full power. The variation of the lift coefficient plotted against the elevator angle, figure 72, shows that the magnitude of longitudinal stability was hardly altered by the deflection of the landing flaps. For suction too, the longitudinal stability was smaller for flight at full power than for zero thrust.

Comparison of the power requirements in flight without and with suction n_G = 3000 rpm.- In figures 73, 74, and 75, the curves of rate of climb and pitch are drawn for comparison; the test points are not marked. In evaluating the rate of climb for full power, it has to be noted that the suction power of about 45 hp was taken from the aircraft engine and thus only 225 hp instead of 270 hp was at disposal at the propeller. In spite of this small motor power, the maximum value of the climbing speed for $\beta_{Kl} = 20^{\circ}$ was almost exactly as high with suction as without. With a landing-flap deflection of 35° for which, in contrast to $\beta_{Kl} = 20^{\circ}$, the flow at the flaps was no longer completely unseparated, the rate of climb with suction decreased slightly. For $\beta_{Kl} = 48^{\circ}$, the difference was still larger. For the operating condition of zero thrust, the difference between the rate of climb values with and without suction, for $\beta_{Kl} = 20^{\circ}$ and 35°, could scarcely be measured. For $\beta_{Kl} = 48^{\circ}$, with zero thrust, the values with suction were somewhat more favorable.

The pitch decreased with setting-in of suction. Especially for flight at full power the decrease in pitch for high lift is rather important. For large airplanes, for instance, flying boats, and application of tricycle landing gear, considerable pitch variations at take-off are utterly undesirable. The AF 2 had, for instance, with full landing-flap deflection and full power, for a dynamic pressure $q = 20\ \text{kg/m}^2$ without suction a pitch of $\vartheta = 16^{\circ}$, with suction, on the other hand of only $\vartheta = 5^{\circ}$. This value $\vartheta = 5^{\circ}$ is also reached for the maximum lift at zero thrust, figure 74. If the suction quantity had been increased until the flow at the flaps adhered, the conditions would have become still more favorable.

Figures 76 and 77, which represent the lift against the angle of attack, show clearly the enormous lift increase due to suction; moreover, the amount of lift increase was only an intermediate stage which might have been considerably improved by increase of the quantity and elimination of rolling stall. The variation of $\frac{dc_a}{d\alpha}$ was not noticeably altered either by landing-flap deflection or suction. The increase in lift was made by change in the zero-thrust direction, in contrast to lift increase, for instance, by the propeller which consists chiefly in an increase of $\frac{dc_a}{d\alpha}$, (cf. figures 58 and 66).

For zero thrust, the longitudinal stability was almost unchanged by setting-in of the suction, figure 78. For full power, a slight increase in static longitudinal stability by suction in case of large landing-flap deflections is noticeable for the AF 2 (fig. 79) as before for the AF 1. (This slight improvement was the more significant because the amount of longitudinal stability in this range was very small, anyway.)

Influence of the suction quantity.- Before beginning the measurements with variation of suction quantity, an attempt was made to increase the output of the blower. The variation in blade setting at the blower wheel brought only a slight gain because, for larger blade-setting angle, the moment increases; however, this was admissible only to a small extent because of the limitation by the coupling. The increase in blower rpm was of considerably greater effect. As mentioned before, this increase could be performed without changes in construction only for zero thrust. In figure 80, the suction quantity is plotted as a function of the blower rpm. The increase of output at standstill for $\beta_{Kl} = 35^{\circ}$ and 48° is almost proportional to the rpm increase. Since coupling, series of shafts, gear, and blower are heavily loaded by the increased power supply, the test series to $n_G = 4200$ rpm were completed in flight only for the maximum landing-flap deflection. For $\beta_{Kl} = 20^{\circ}$ and 35°, the variation in suction quantity was made in the range $n_G = 2000$ rpm to $n_G = 3000$ rpm.

A dependence of the suction quantity on the flight speed for the AF 2 could not be observed then, either, although the measuring accuracy was very high as shown by the small dispersion of the test points in figures 81 and 82. The suction quantity in flight is drawn in figure 80. At first, it is somewhat surprising that, for $\beta_{Kl} = 20^{\circ}$, more quantity was sucked off in flight than at standstill. Probably in flight a slight negative pressure was produced at the exit of the sucked-off air by the flow about the fuselage; thus, this negative pressure somewhat increased the output.

The rate of climb was hardly influenced by the variation in suction quantity, figure 83 Only for $\beta_{Kl} = 48^{\circ}$ and $n_G = 4200$ rpm, a slight decrease of the values may be observed. Tuft investigations showed that the flow completely adheres at the flap deflected by 20° as soon as $n_G = 2000$ rpm. The variation of the blower rpm between $n_G = 2000$ and $n_G = 3000$ for this flap angle had no measurable influence on the pitch. The curve already shown in figure 64 was obtained. For $\beta_{Kl} = 35^{\circ}$ and 48°, the pitch values shown in figures 84 and 85 resulted.

For the large landing flap deflections of 35° and 48°, the lift in the indicated range decreased if the rpm was reduced, figures 86 and 87. The influence of suction for the smallest blower rpm measured, $n_G = 2000$, was of noteworthy magnitude for the AF 2, too. The strong increase of the lift augmenting effect of suction for the high blower rpm and $\beta_{Kl} = 48^{\circ}$ (fig. 87) was probably caused by the fact that the flow at the landing flap only then started to adhere more closely. As said before, complete adherence was not yet attained for $n_G = 4200$ rpm. Nevertheless $c_{a_{max}} = 3.8$; therewith the value of $c_{a_{max}} = 1.9$ for the same operating condition without suction is exactly doubled. A further increase to about $c_{a_{max}} = 4$ to 4.5 appears entirely feasible by a relatively small increase in suction quantity.

The dependence of the lift on the suction quantity is represented in the figures 88, 89, and 90. For $\beta_{Kl} = 20^{\circ}$, no measurable change in rate of climb and pitch could be determined in the range of rpm. Thus the lift coefficient in the measured c_Q range was constant. Since the drop from these values to the test points without suction was not determined, the probable variation was drawn in dashed lines. For $\beta_{Kl} = 35^{\circ}$ and 48°, there is rather good agreement between the position of the test points without suction ($c_Q = 0$) and the course of the curves. The lift coefficient attained for the same angle of attack is, starting from approximately $c_Q = 0.004$, proportional to the quantity coefficient.

The variation in suction quantity had no influence on the magnitude of the longitudinal stability as one can see, for $\beta_{Kl} = 48^{\circ}$, from figures 91 and 92. The more blower rpm and, hence, suction quantity increase, the more, for equal dynamic pressure, the elevator must be pressed down. Thus in the high-lift range also, a considerable reserve in elevator deflection was at disposal so that the elevator was sufficient even for a location of the center of gravity further toward the front.

Summarizing the flight-performance measurements on the AF 2, figure 93, gives the polars of the airplane. The results of a test series with $\beta_{Kl} = 35^{\circ}$ and $n_G = 4200$ rpm for zero thrust are here included. The course of the curves measured for zero thrust agrees quite well with the parabola of the induced drag. The additional drag, consisting of profile drag, drag of fuselage, landing-gear mutual interference and suction, was almost independent of the angle of attack.

IV. COMPARISON OF THE FLIGHT PERFORMANCES OF AF 1, AF 2, AND Fi 156

It suggests itself to include for the comparison of the results on the two airplanes with suction another airplane on which other means for lift increase have been used to a high degree. The airplane Fi 156 (Fieseler-Storch) seems actually predestined for this purpose. The order of magnitude of the three airplanes is almost the same. In the table on page 36 the numerical data for the Fi 156 are inserted in the last column: fuselage and tail surfaces of the Fi 156 were applied without change to the AF 2.

In spite of all this, such a comparison involves certain dangers. Thus, it is emphasized at this point that the purpose of the two planes with suction was quite different from that of the Fi 156. The Fieseler-Storch was a general-purpose airplane designed for the special use of a liaison aircraft. Probably it would have been possible to increase, for instance, for the Fi 156, the attainable lifts somewhat more, by attaching less importance to the flight characteristics. The two airplanes with suction were used purely for testing purposes. It was their purpose to investigate the problem of whether suction may be used for lift increase in flight, too. Thus, it is completely misleading to regard the airplanes with suction perhaps as competition for the Fi 156. In view of the expenditure, suction probably can be applied only for larger airplanes. The following comparisons are to be understood with these reservations.

The flight performances of the Fi 156 were taken partly from the data of S. Hörner (reference 49), partly they stem from measurements of the author, which agree rather well with Hörner's results. The full-power tests are not suitable for comparison since the power loadings of the three airplanes are too different. Only the pitch for which the maximum lift values were attained with full power is noteworthy. It was for the AF 1 $\approx 13^{\circ}$, for the AF 2 $\approx 16^{\circ}$, for the Fi 156 $\approx 37^{\circ}$. The desirability of the small pitch value for high lift and full power in large airplanes has been pointed out before.

The best comparison can be made for flight performances attained with power off or zero thrust, respectively. The lifts here in question were produced by the wing without interference by the propeller. The measurements for the maximum deflection of the landing flaps in each case were taken as basis. The outer landing flaps on the aileron were then deflected for the AF 1 by 40°, for the AF 2 by 33°, and for the Fi 156 by 15°. Figure 94 shows a comparison of the profiles of the three airplanes near the fuselage on the same scale. Figure 95 gives the lift coefficient against the angle of attack. The lifts of the AF 1 and AF 2 without suction were of about the same magnitude as that of the Fi 156. The lift increase caused by turning-on of the suction was extraordinary. The better performance of the AF 2, compared to the AF 1, stems to a small part from the difference between power off (AF 1) and zero thrust (AF 2). The maximum lift coefficient of the Fi 156 was larger by approximately 0.1 for zero thrust than with power off.

In flight, suction fully lived up to the expectations evoked by the wind-tunnel tests; moreover, the AF 1 and AF 2 were first-test planes which certainly do not yet represent the optimum. On the other hand, with respect to application of slot and flap, the Fi 156 was, as it were, a final stage of the development. A considerable improvement of the existing performances by means of these expedients can no longer be expected.

V. GENERAL CONSIDERATIONS REGARDING APPLICATION OF SUCTION

The application of suction research is still in its beginnings, although rather promising and important results start to evolve. Almost all existing reports of the literature enumerated below deal with investigation of the profile characteristics. So far there exists only a small number of publications about, for instance, three-dimensional phenomena, influence of the suction-quantity distribution along the span, investigation of a complete model, model tests regarding flight properties, etc.

If one decides to apply suction, he had better confine himself with utmost accuracy to the data of the research institutes. It would be bold and absurd to want to obtain successes with suction in flight, for instance, with a profile of 13-percent thickness at a time when, in the laboratory, with much labor and after long and difficult testing, only for instance 17 percent has been reached (in the meantime, good results were obtained in the wind tunnel for 12 percent). Tests of this type are certainly a priori condemned to complete failure. One should take to heart the utterance of Professor Betz who dealt for many years with friction-layer and suction problems: "According to all experiences made with friction-layer matters, one always is too optimistic. For the most part, the methods one has thought up cannot be realized at all; sometimes they yield a small effect, and only very rarely the results are in agreement with one's expectations" (reference 50). On the other hand, pessimism is entirely uncalled for, as the present flight tests prove.

The remodelling of existing airplanes into planes with suction appears inexpedient. Generally, one is forced to make too many compromises. At any rate, full success may be expected only when application of suction with its special requirements has already been taken into consideration in the design of the airplane. Flow losses within the suction arrangement have to be kept at a minimum with the greatest care. In this field, more can be accomplished; even the smallest increase in suction quantity produces an improvement in performance. Thus, for instance, the sealing of the tiny slot between wing and landing flap on the pressure side of the AF 2 produced a quite noticeable effect.

The aileron problem still requires a considerable amount of work. The Gropler aileron used for the AF 1 and AF 2 does not represent a final solution. For full suction, it may meet the requirements; however, in slow flight without suction, its effect is insufficient.

Neither will the object be attained by the suggestion to control the motions about the longitudinal axis by different throttling of the suction quantity at the two wing tips. First, this method will be affected by the deficiency of all aileron controls which operate with lift interruption: the time lag of the rolling motion behind the control deflection. In spite of greatest efforts, interrupter control has so far not been fully developed. Second, the main difficulties do not lie in aileron control with suction turned on, but just in control at suction stoppage. The junction of the aileron to the wing so as to obtain proper suction in spite of freedom of deflection poses a special constructive and aerodynamic problem. The task is perhaps facilitated if the air is not sucked off but blown out in the aileron region. Due to the directional effect at disposal in blowing out in contrast to sucking off, it is probably easier to maintain the flow at the aileron unseparated for all deflections. In practice, one will, anyway, not want to relinquish the energy contained in the sucked-off air, as has already been pointed out. The related research work of W. Schwier shows that as high, if not higher, lift values for equal quantities and powers may be attained by blowing-out of air as by suction.

It will be possible to work on and to answer part of the still unsolved tasks and problems with the AF 2. For the development of a second wing, I have set up from a pilot's and experimental-technical point of view, the following desired features and requirements:

1. Increase in wing loading

2. Improvement of aileron effectiveness

3. Attainment of stable conditions by more uniformly curved wing contour

4. Increase of suction quantity

The increase in wing loading facilitates the test conditions, aside from the fact that it complies with today's trend of development. The following data may serve as a measure for the increase in wing loading: a lift coefficient of $c_a = 4$ is to be attained for the speed at which the present wing unit has the coefficient $c_a = 3$. The higher dynamic pressure can be measured with less difficulty and more accuracy. On the other hand, one has to reckon with an increase in control effectiveness. The increase in aileron effect is absolutely required in order to attain the high lifts, also for unsteady weather conditions. Stable conditions must exist for attainment of the actual performances of wing and suction in practice. The increase in suction quantity may be realized by increase in blower power and also by improvements of the flow conditions in wing and fuselage.

According to these suggestions, my collaborator, I. K. Grothey, director of the construction group, designed a second wing for the AF 2, figure 96. In the following table, the numerical data for the now existing and tested first wing unit and for the new design are compared. Nothing has been settled yet concerning the suction-technical aspect of this design. From this point of view, it will have to be decided whether it appears suitable and promising to construct such a wing.

Quantity	Dimension:	Wing Unit I	Wing Unit II
Span	m	15.25	12.5
Wing area	m^2	24.1	18.2
Aspect ratio		9.65	8.6
Flying weight	kg	1350	1350
Surface loading	kg/m^2	55	74
Taper ratio		0.3	0.57
Landing-flap chord			0.27 t
Aileron Chord			0.27 t

VI. SUMMARY AND CONCLUSIONS

The present report contains the experiences gathered through tests on two airplanes with suction. The measurements show that by the first application of suction, high lifts were obtained never before attainable by other means. At take-off, a large reduction of the rolling distance and the take-off speed was attained whereas the gain in take-off distance was insignificant for both airplanes. Certain deficiencies in the flight characteristics of both airplanes are pointed out; however, they were not caused by the application of suction.

Finally, the answer is given concerning the problems (page 5) which were to be clarified by means of the airplanes with suction:

1. Suction during flight is extremely effective. By application of suction, the lift coefficients of the wing without propeller influence could be doubled compared to the maximum values so far.

2. The flight characteristics are not influenced unfavorably by the suction; however, it will be necessary to scrutinize the control effectiveness, in view of the small dynamic pressures obtainable by suction.

3. The sudden stop of suction was, in both airplanes, harmless and did not produce any dangerous flight behavior.

4. A comparison of wind-tunnel results with flight-test values exceeds the scope of the present report. Such a comparison

is being made in a special report by the Boundary-Layer Research Group of the Wind Tunnel Institute.

Translated by Mary L. Mahler
National Advisory Committee
for Aeronautics

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TABLE I

Measuring quantity	Dimension	AF 1	AF 1 After re-construction	AF 2	Fi 156
Span	m	13.00	13.26	15.25	14.25
Length	m	11.19	11.34	9.76	9.61
Height	m	3.15	3.15	3.50	3.50
Wing area	m^2	25.0(without aileron)	25.0	24.1	26.0
Aspect ratio	-	6.8	7.0	9.65	7.8
Weight empty (aircraft equipped but not loaded)	kg	960	1030	1115	978
Flight weight	kg	1310	1373	1340	1260
Wing loading	kg/m^2	52.4	55.0	55.6	48.5
Position of center of gravity (t at 0.225 b from center)	-	0.28t	0.30t	0.35t	0.36t
Motor power (maximum power)	hp	150	150	270	240
Power loading	kg/hp	8.74	9.16	4.97	5.25
Profile	-	Gö.683	Gö.683	NACA 6218g	
Profile thickness	-	0.20-0.176	0.20-0.176	0.18	0.15
Sweepback	deg	3.5	3.5	0	0
Dihedral	deg	2.0	2.0	1.0	0.5
Wing Twist	deg	5.5(rectilinear from b/4 to end)		0	0
Angle of wing-setting (wing chord - fuselage)	deg	4.0	4.0	1.0	2.5
Inner flap chord	-	0.24t	0.24t	0.19t	0.25t
Outer flap chord	-	0.26t	0.30t	~0.25t	-
Aileron area	m^2	5.2	2.02	1.7	1.44
Horizontal stabilizer area	m^2	2.98	2.98	1.88	1.88
Elevator area	m^2	1.87	1.87	3.12	3.12
Vertical stabilizer area	m^2	0.70	0.70	0.58	0.58
Rudder area	m^2	1.20	1.32	1.52	1.52
Area of end plate	m^2	1.10	-	-	-
Area of landing flap	m^2	4.00	3.28	2.92	2.20
Propeller diameter	m	2.2	2.2	2.6	2.6
Propeller pitch	m	1.18	1.18	variable	1.43
Suction power	hp	18	18	~45	-
Blower diameter	m	0.75	0.75	0.59	-
Blower rpm (standard)	rpm	2100	2100	3000	-

NACA

Figure 1.- Flow about a circular cylinder without suction, initial state.

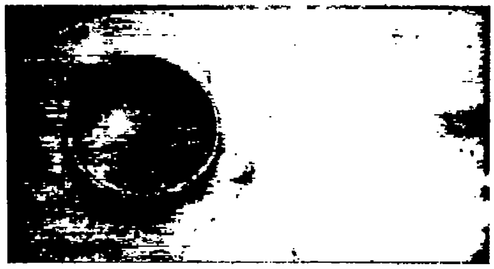


Figure 2.- Flow about a circular cylinder without suction, steady state.

Figure 3.- Flow about a circular cylinder with suction, initial state.

Figure 4.- Flow about a circular cylinder with suction, steady state.

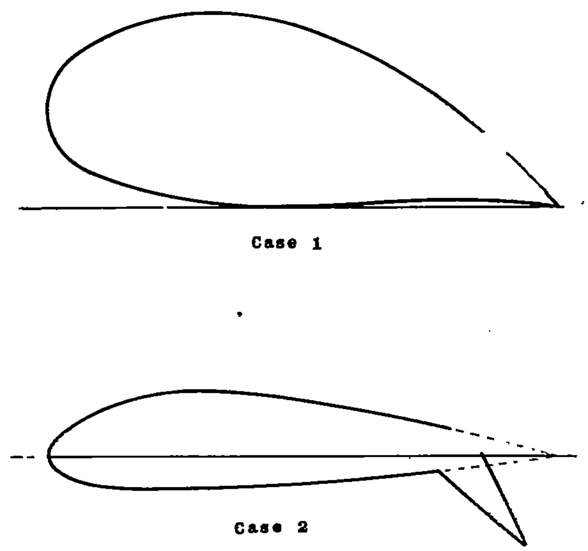


Figure 5.- Two possible configurations for suction.

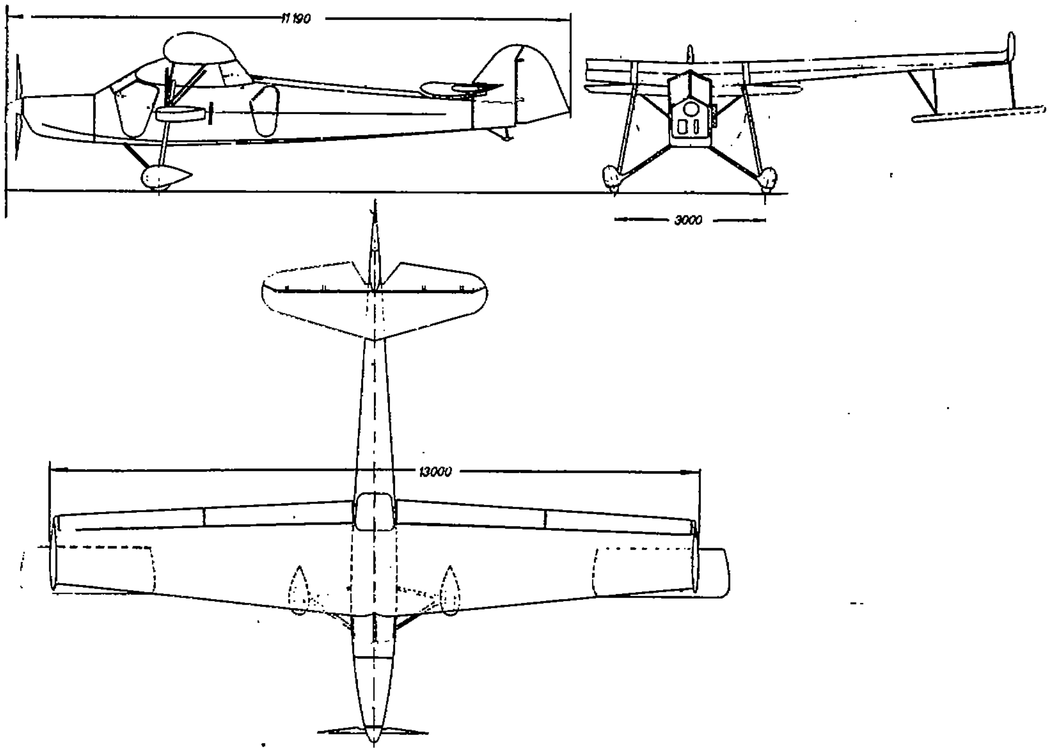


Figure 6.- Three-view diagram of the AF 1, original design.

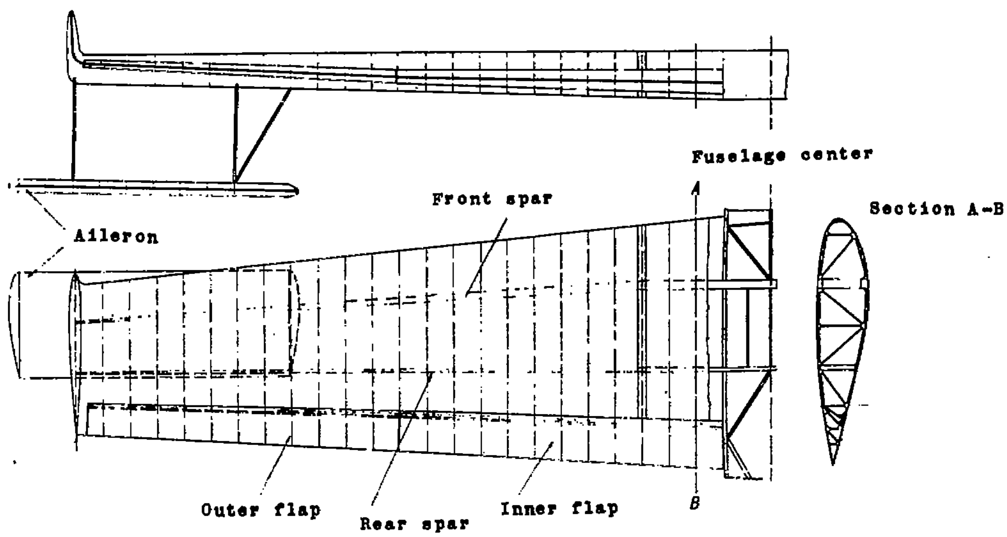
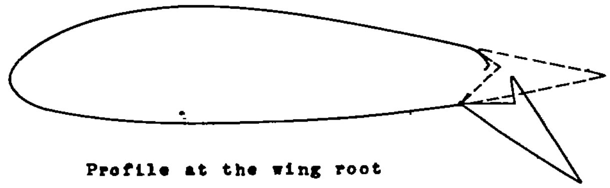


Figure 7.- Wing of the AF 1, original design.



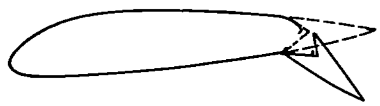


Figure 8.- Profile of the AF 1.

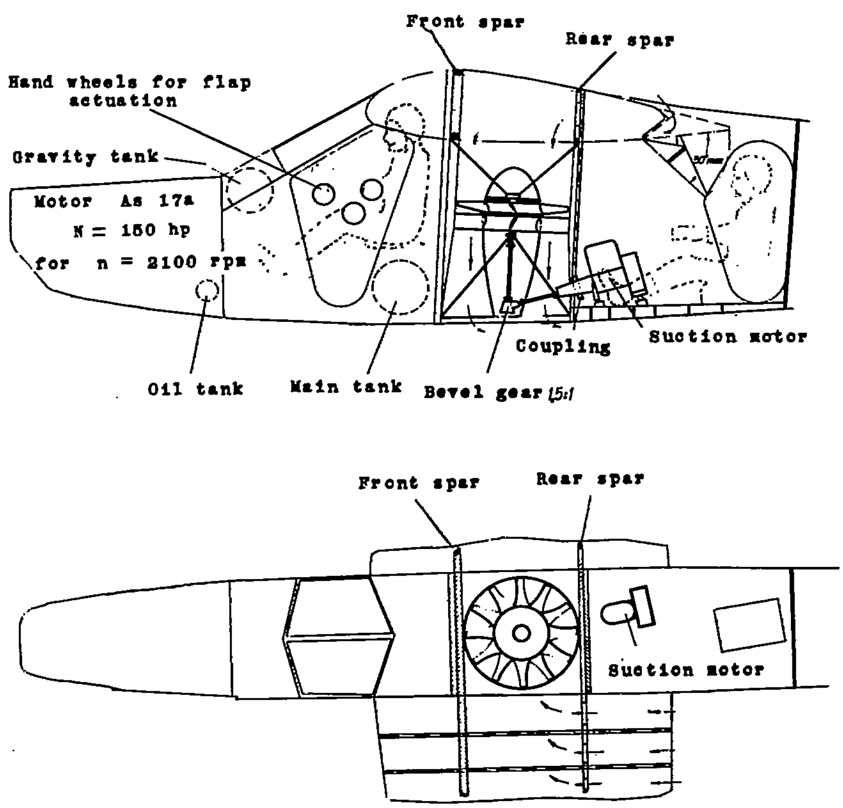


Figure 9.- Suction arrangement of the AF 1.

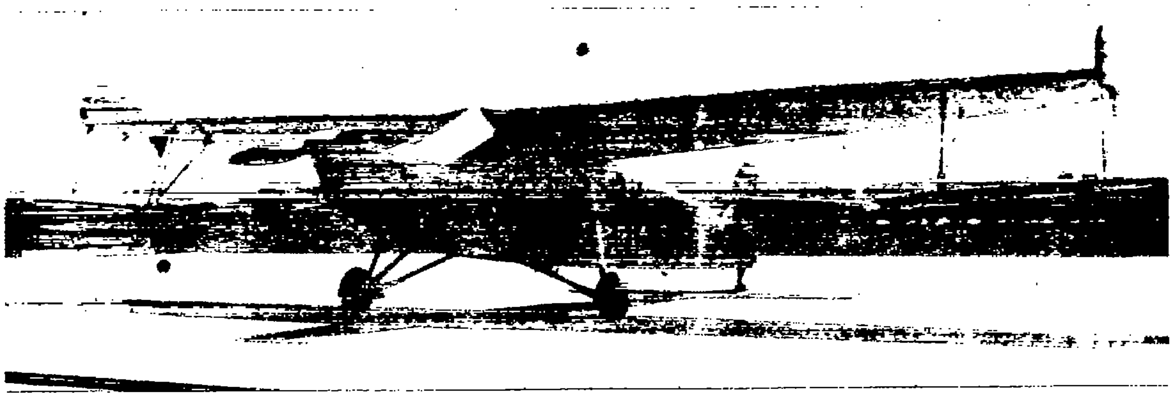


Figure 10.- AF 1, original design.

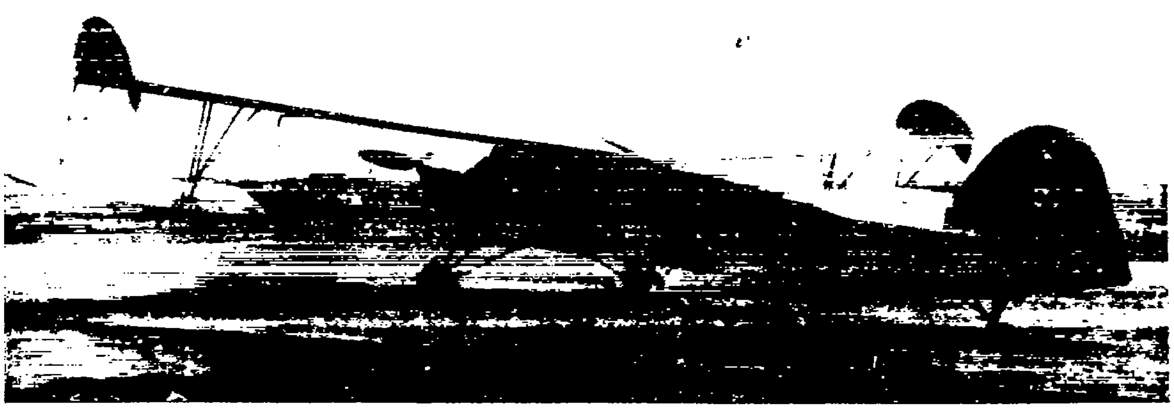


Figure 11.- AF 1, original design.

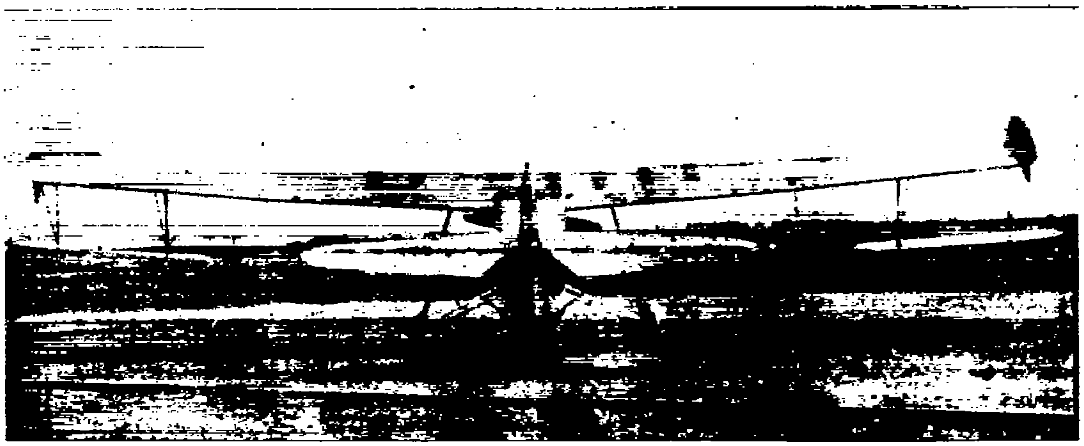


Figure 12.- AF 1, landing flaps retracted.

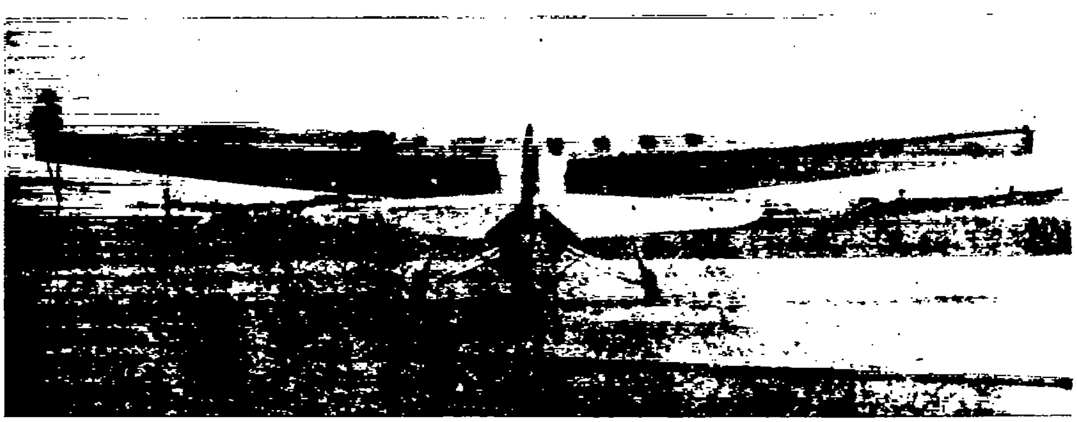


Figure 13.- AF 1, landing flaps fully deflected.

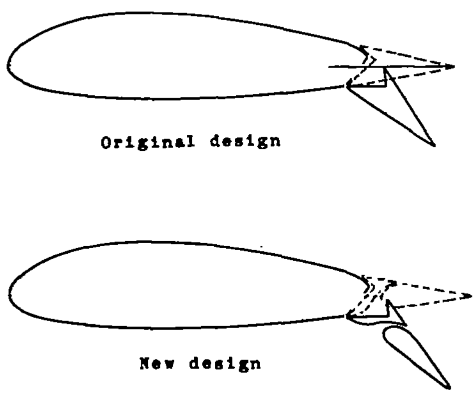


Figure 14.- Reconstruction of the AF 1 profile section in the region of the outer landing flap.

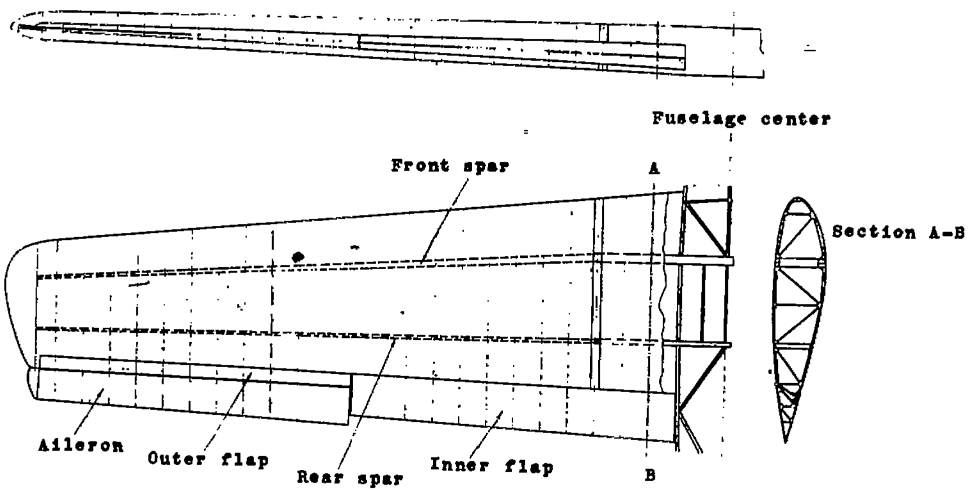


Figure 15.- Redesigned wing of the AF 1.

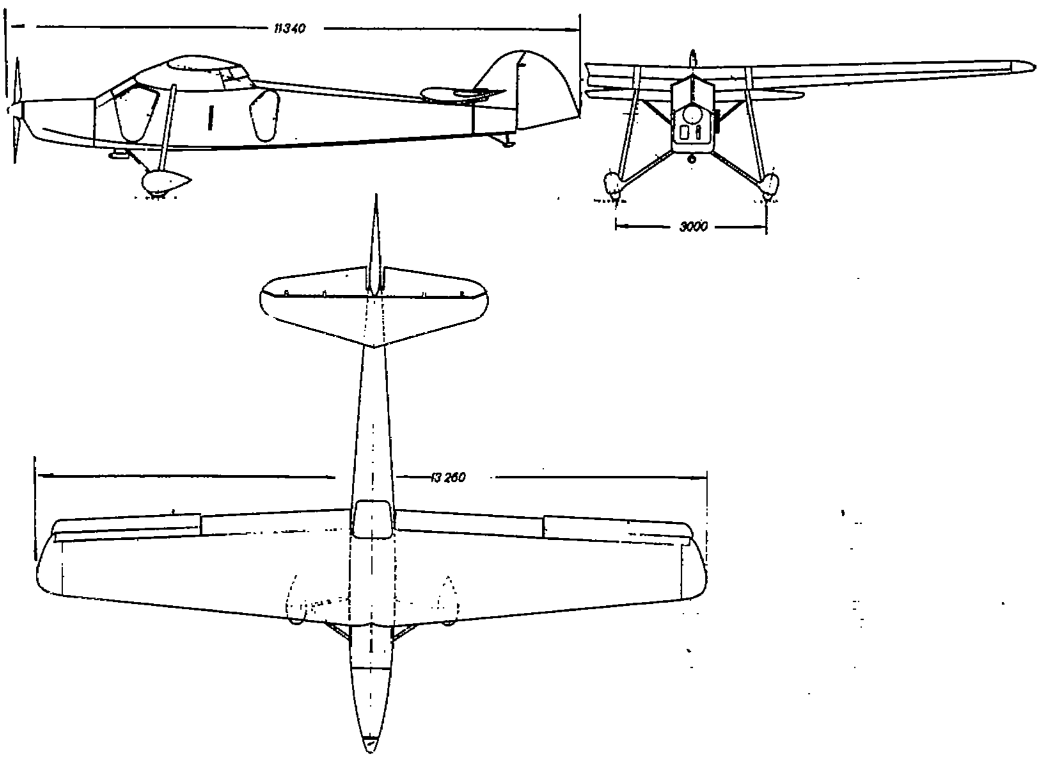


Figure 16.- Three-view drawing of the AF 1 after alteration.

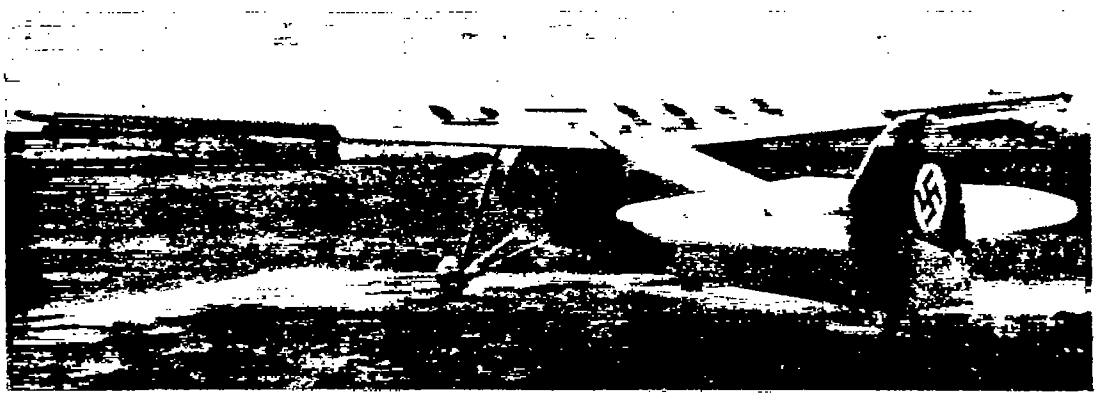


Figure 17.- AF 1 after alteration.

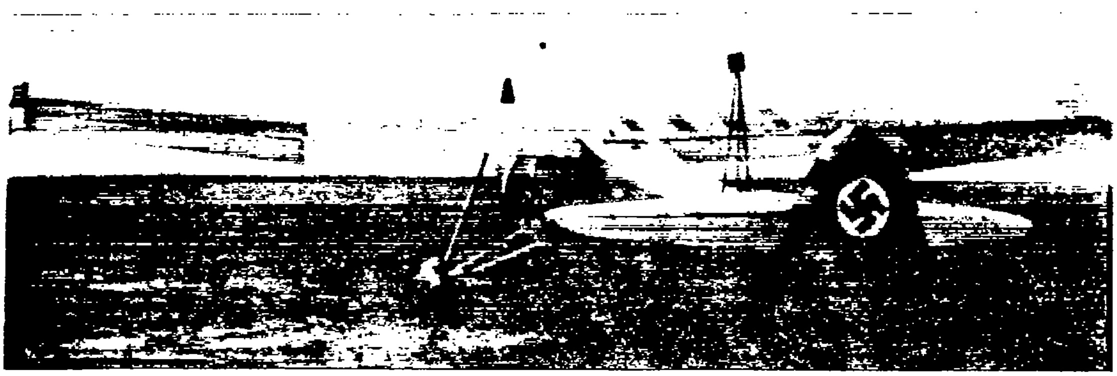


Figure 18.- Arrangement for the tuft investigations.

Figure 19.- Installation of the "log" in front of the wing of the AF 1.

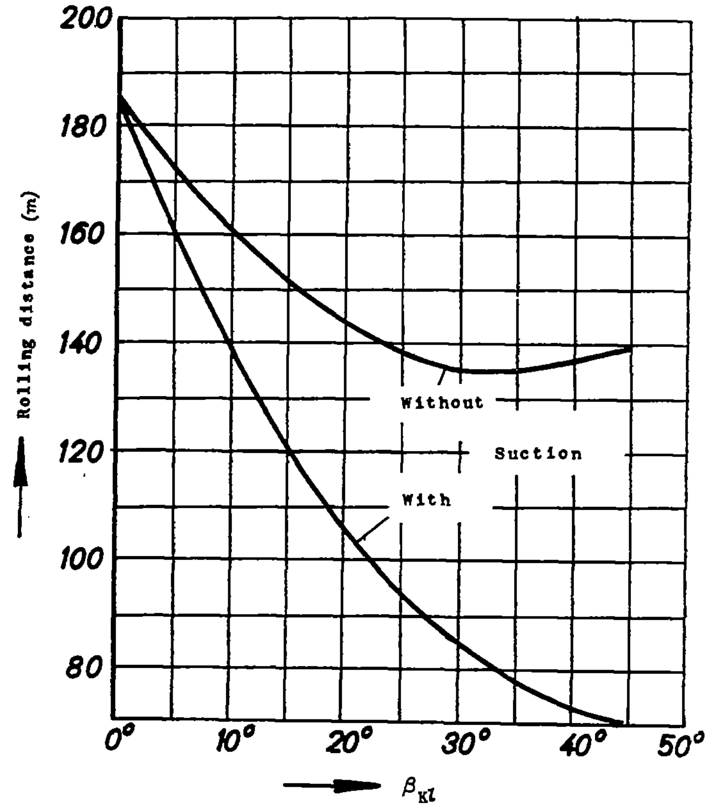


Figure 20.- Rolling distance of the AF 1.

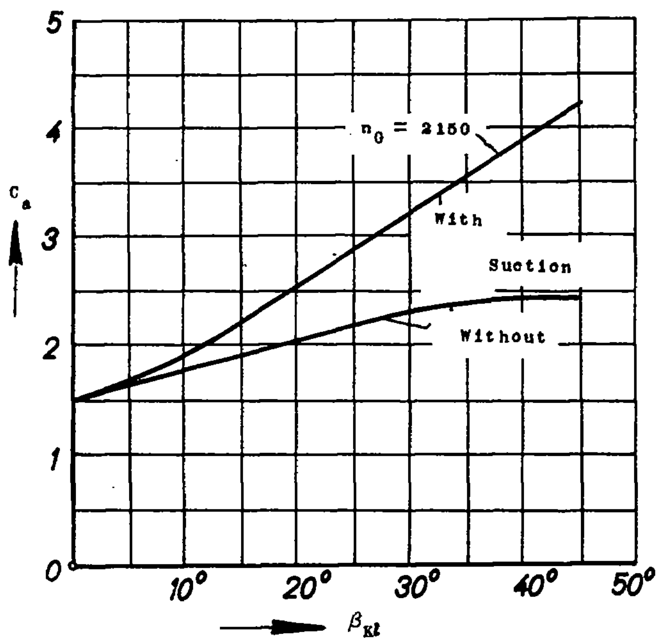


Figure 21.- Lift coefficient for take-off of the AF 1.

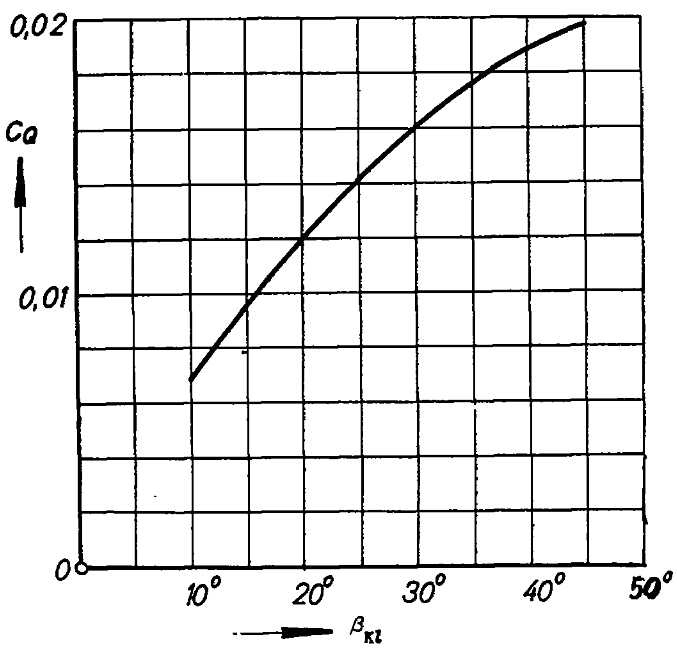


Figure 22.- Quantity coefficient for take-off of the AF 1 for full power of blower motor. n_G = 2100.

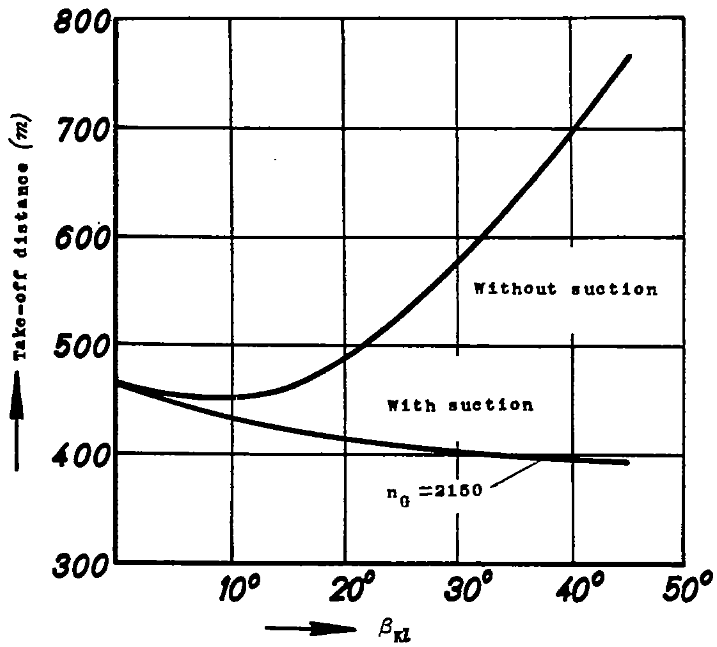


Figure 23.- Take-off distance of the AF 1 from standstill to 20 meters altitude.

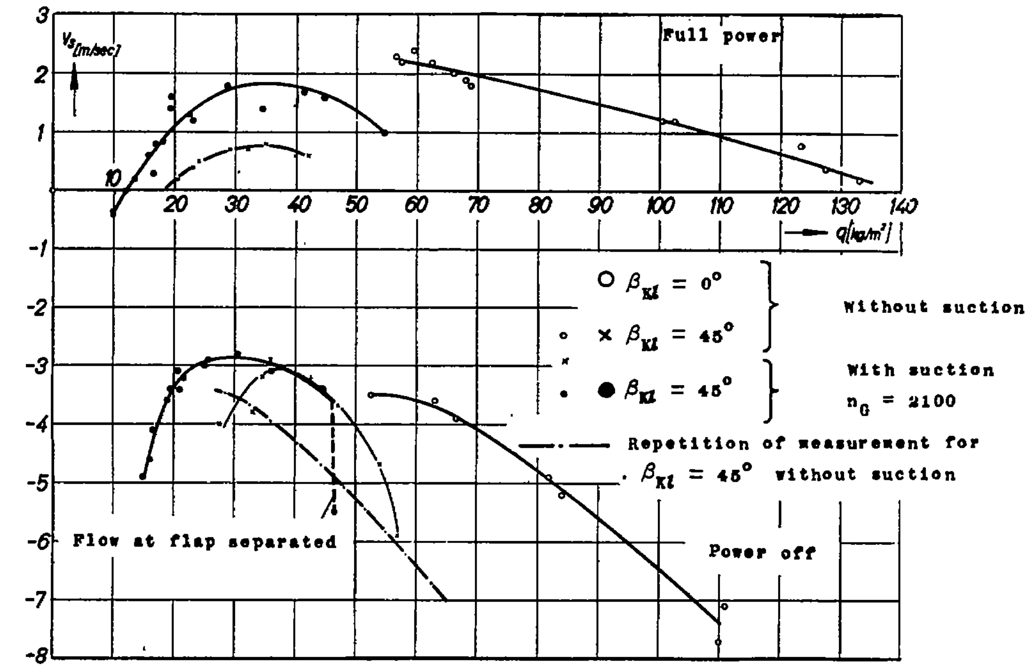


Figure 24.- Rate of climb of the AF 1.

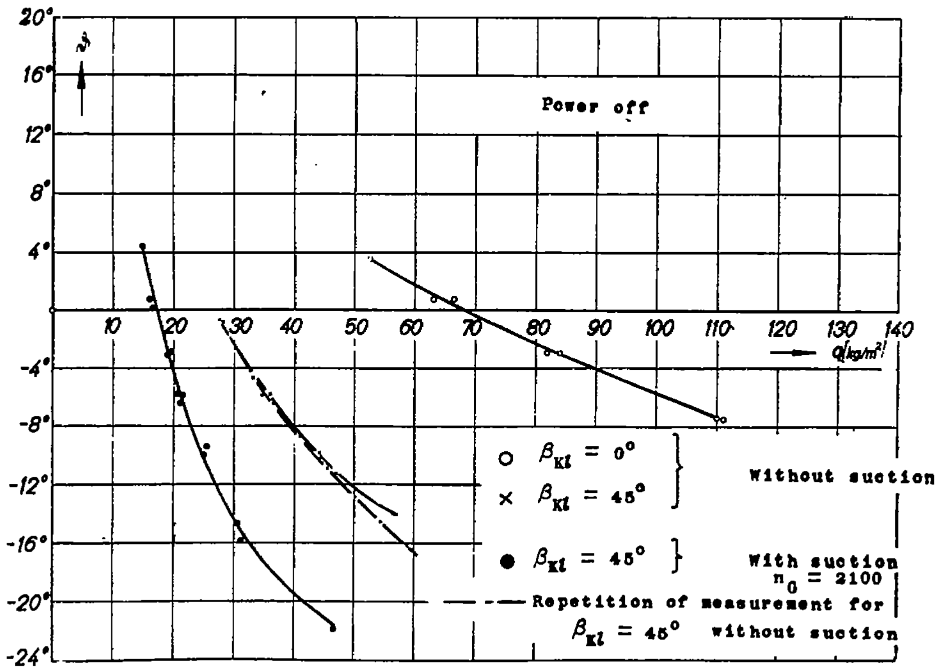


Figure 25.- Pitch of the AF 1 for power off.

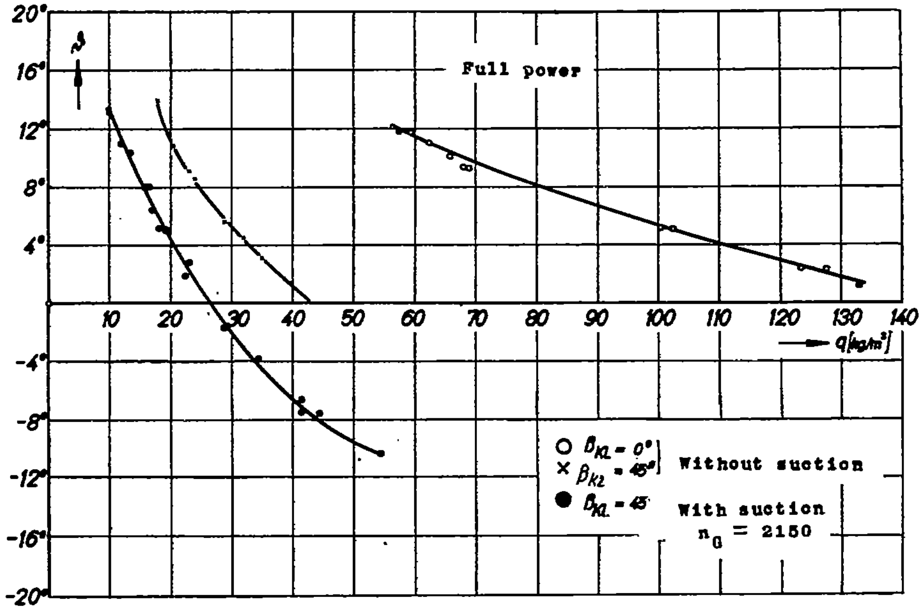


Figure 26.- Pitch of the AF 1 for full power.

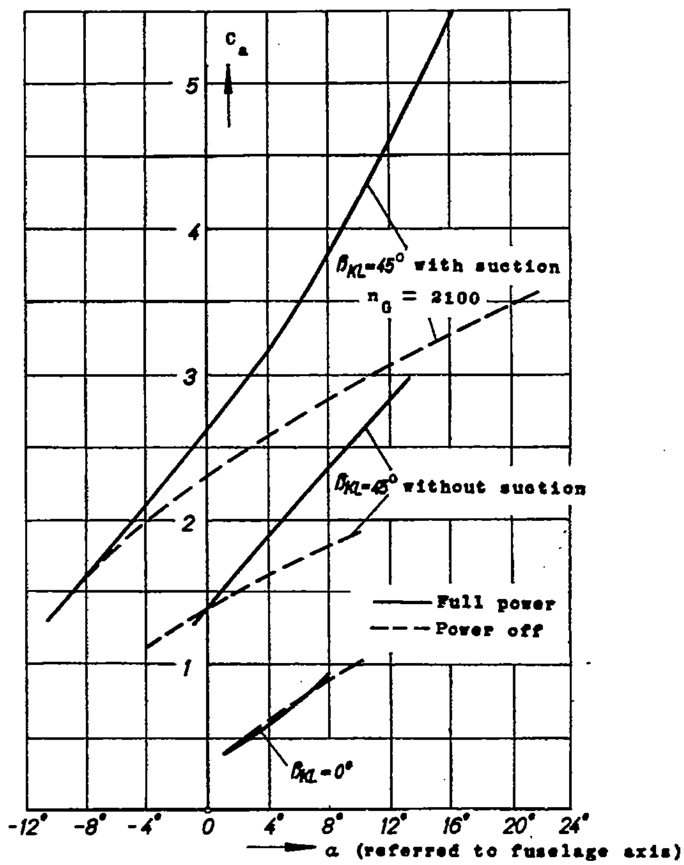


Figure 27.- Lift of the AF 1 as a function of the angle of attack.

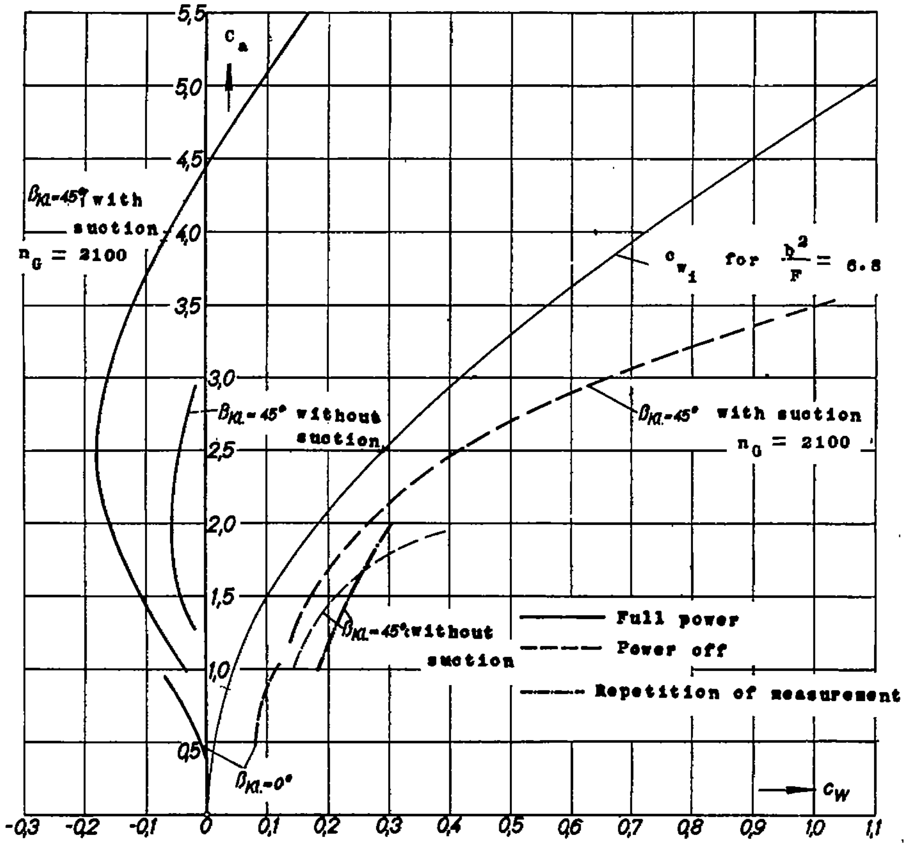


Figure 28.- Polars of the AF 1.

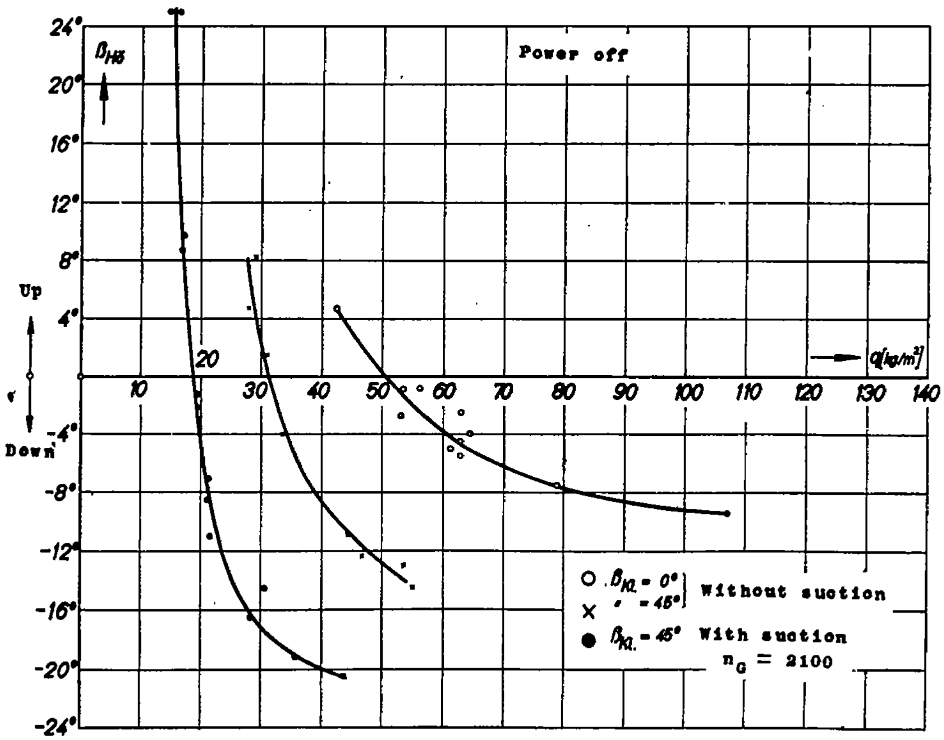


Figure 29.- Elevator deflection of the AF 1 for power off.

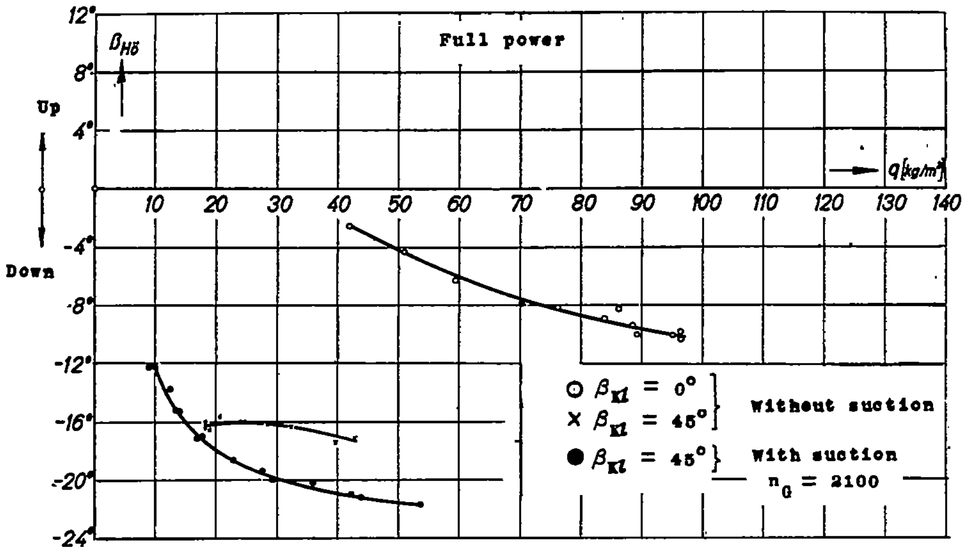


Figure 30.- Elevator deflection of the AF 1 for full power.

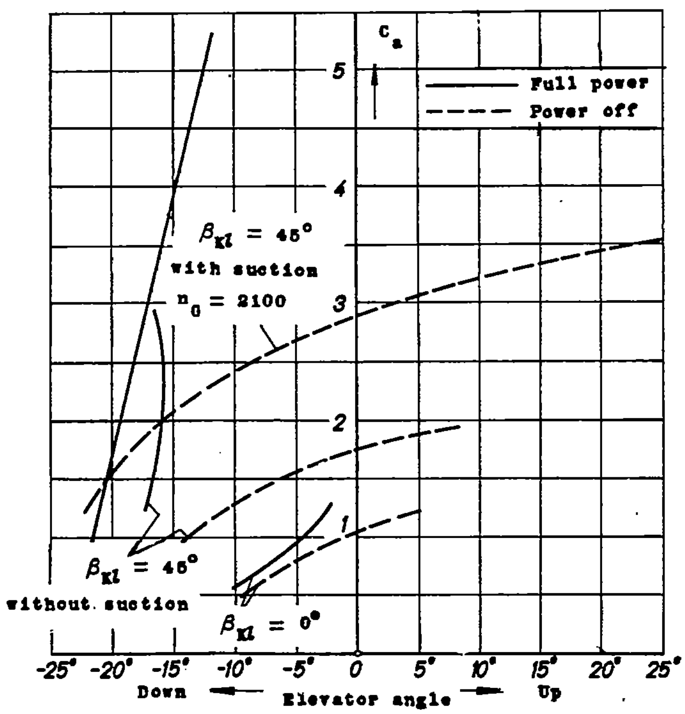


Figure 31.- Lift coefficient of the AF 1 as a function of the elevator deflection.

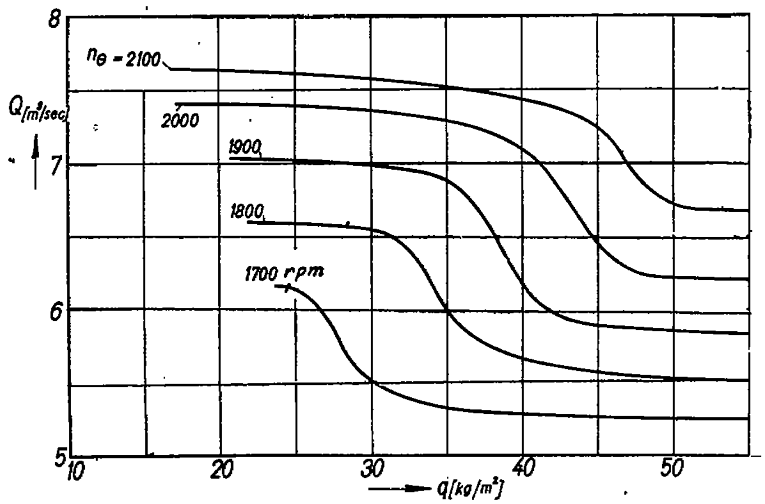


Figure 32.- Suction quantity of the AF·1 for $\beta_{Kl} = 45^{\circ}$ and power off.

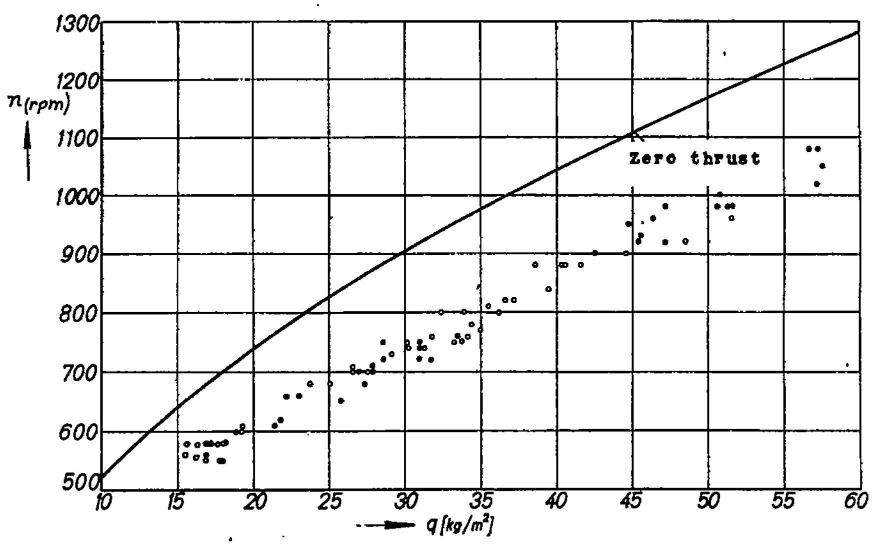


Figure 33.- Rpm of the idling aircraft engine of the AF 1.

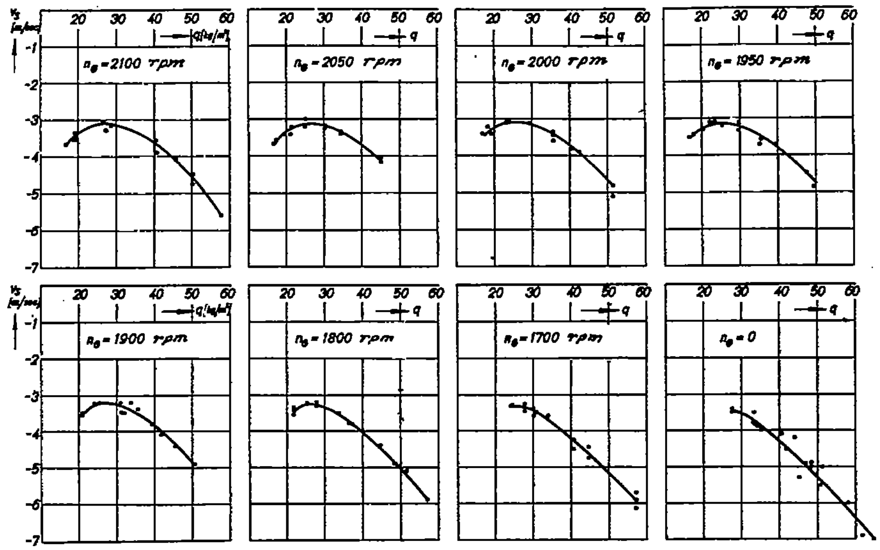


Figure 34.- Rate of climb of the AF 1 for various suction quantities, $\beta_{Kl} = 45^{\circ}$, power off.

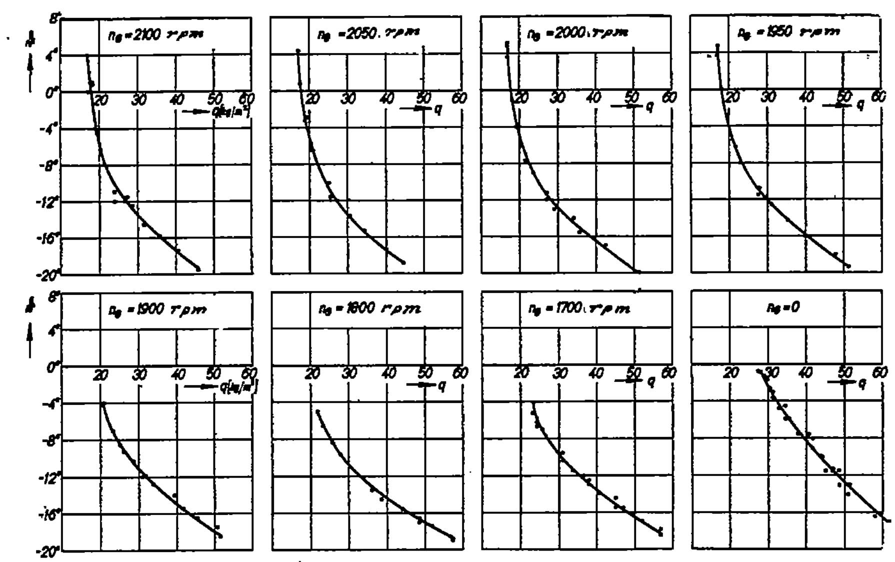


Figure 35.- Pitch of the AF 1 for various suction quantities, $\beta_{Kl} = 45^{\circ}$, power off.

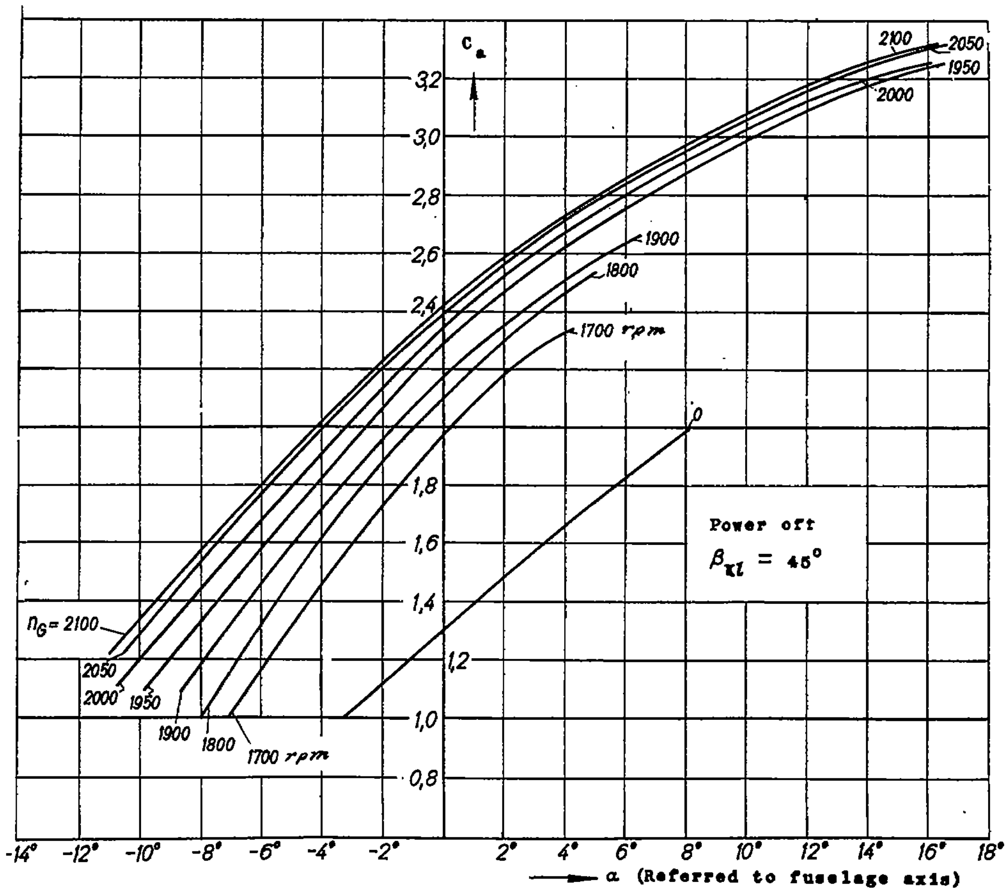


Figure 36.- Lift coefficient of the AF 1 for various suction quantities, $\beta_{Kl} = 45^{\circ}$, power off.

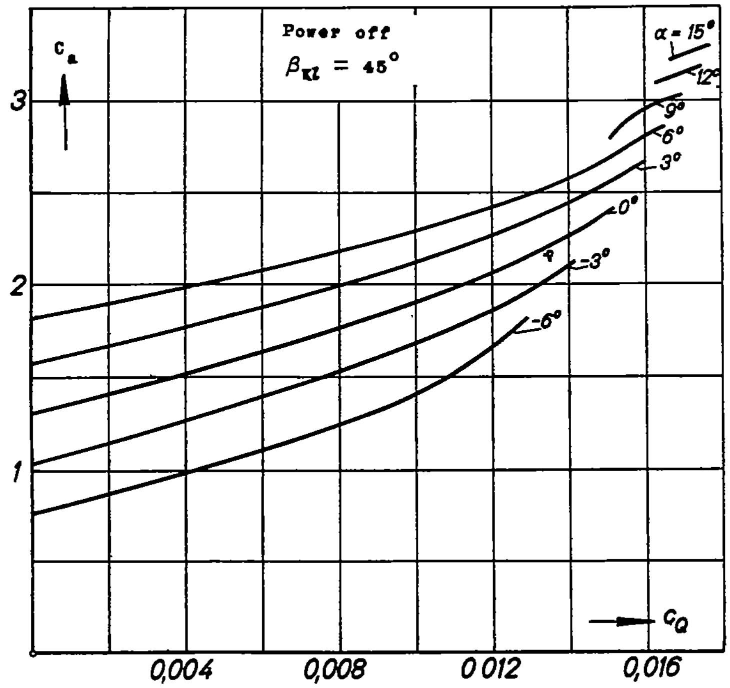


Figure 37.- Lift coefficient of the AF 1 as a function of the quantity coefficient, β_{Kl} = 45°, power off.

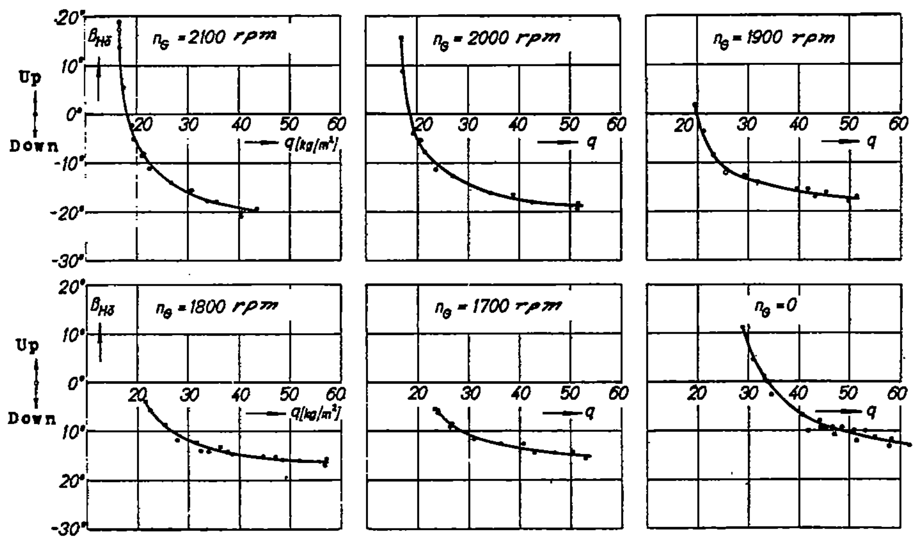


Figure 38.- Elevator deflection of the AF 1 for various suction quantities, β_{Kl} = 45°, power off.

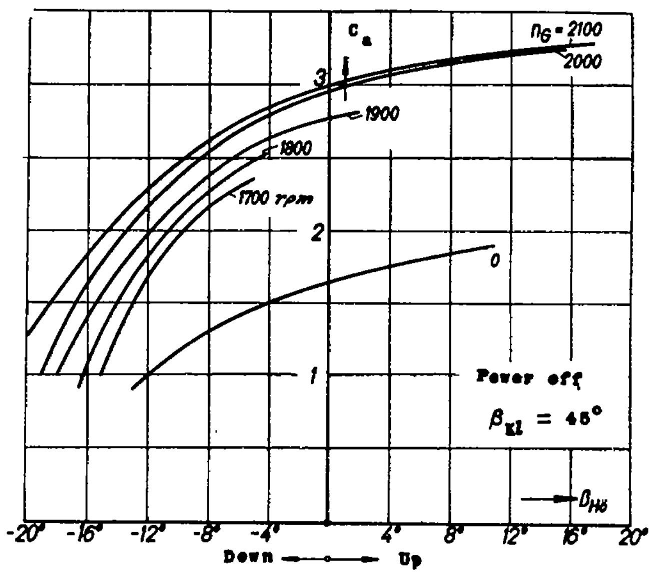


Figure 39.- Lift coefficient of the AF 1 as a function of the elevator deflection for various suction quantities, $\beta_{Kl} = 45^{\circ}$, power off.

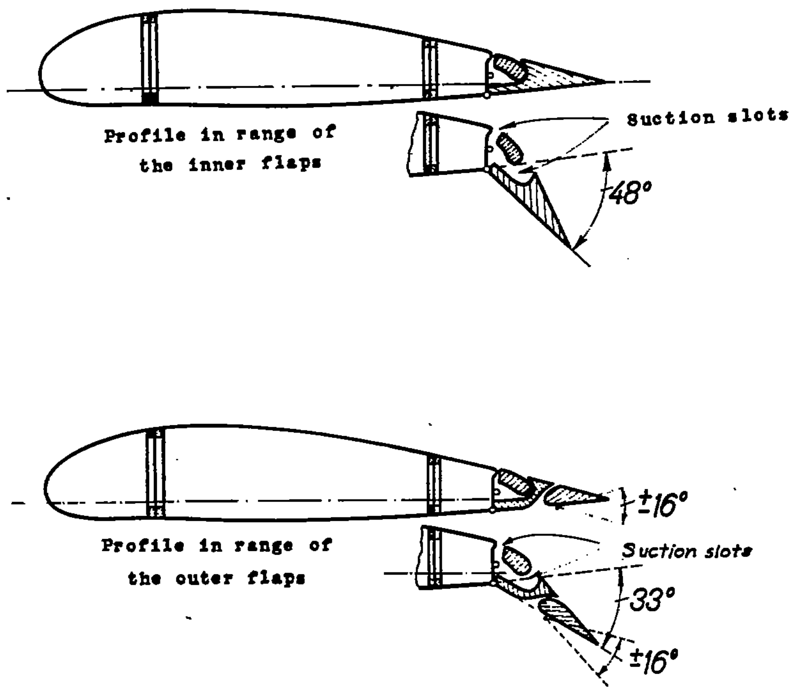


Figure 40.- Profiles of the AF 2.

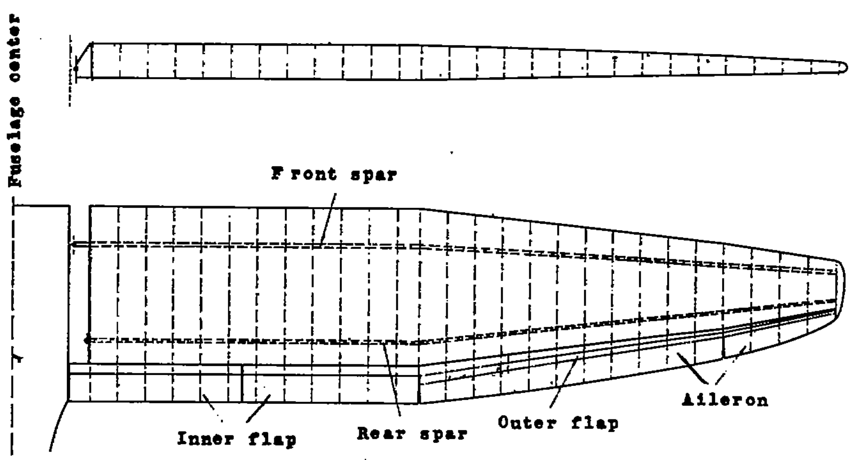


Figure 41.- Wing of the AF 2.

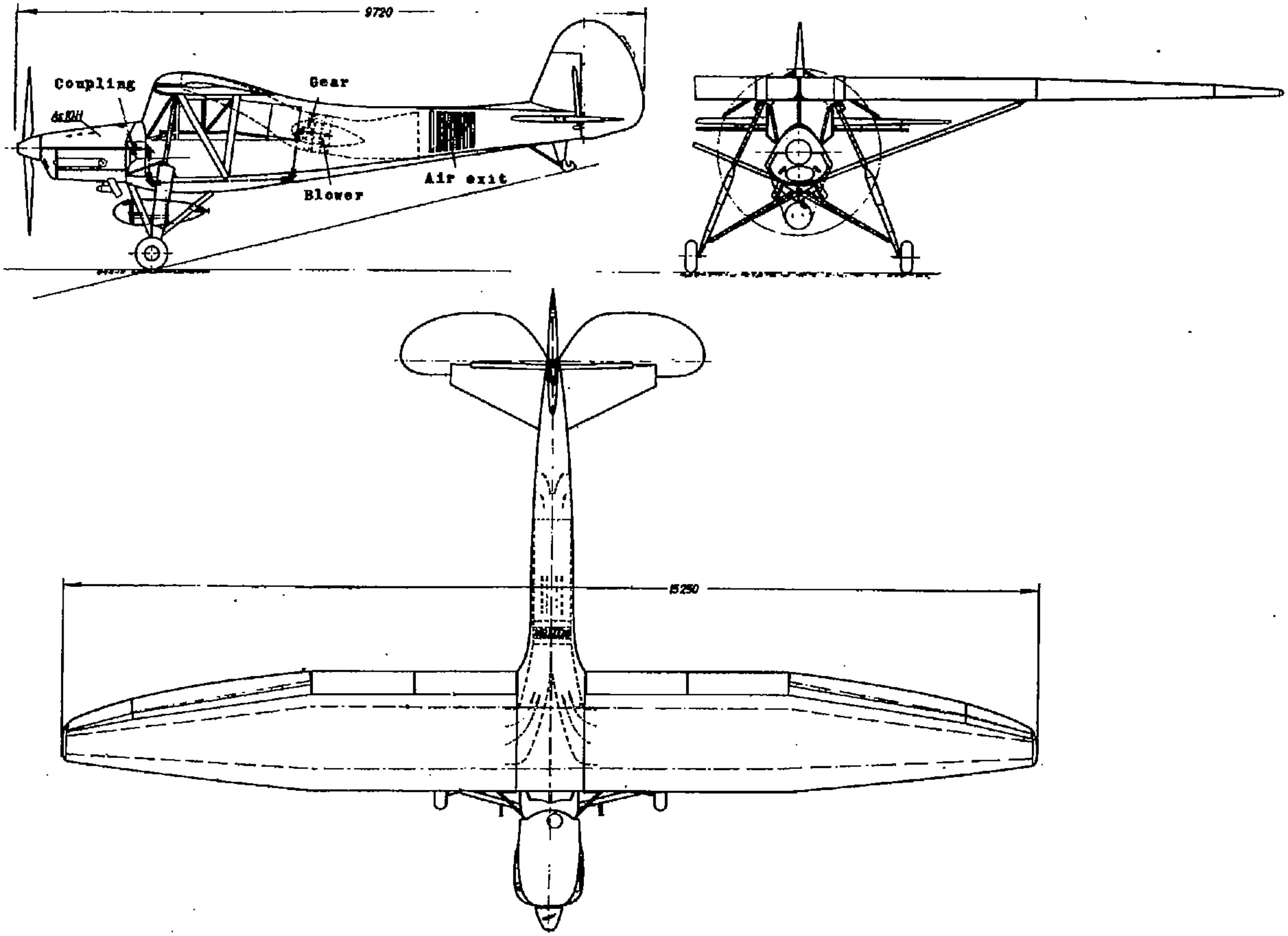


Figure 42.- Three-view drawing of the AF 2.

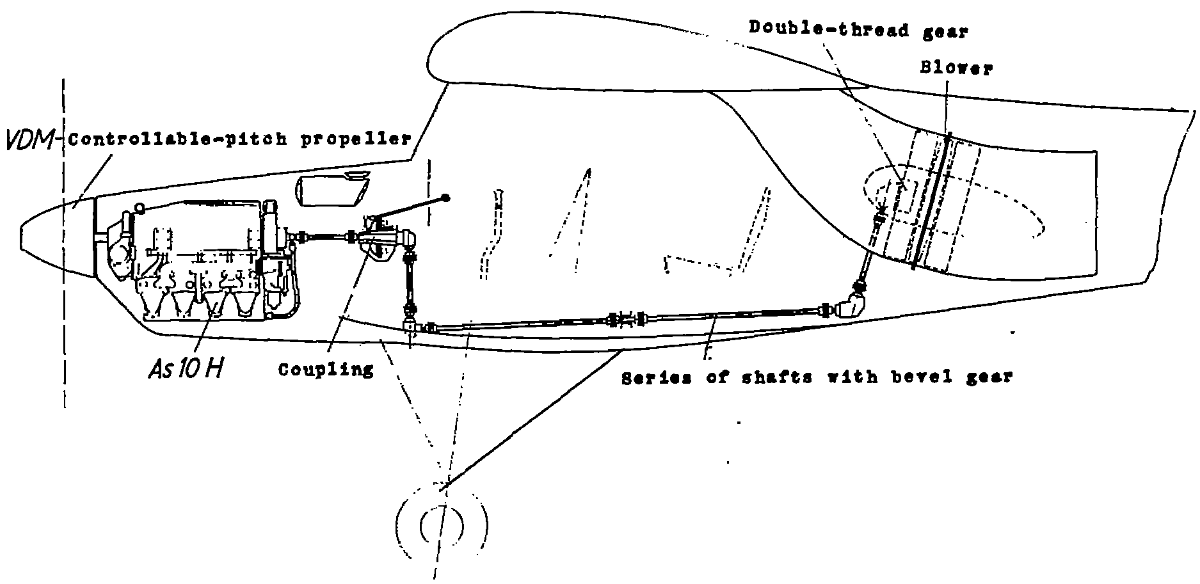


Figure 43.- Suction arrangement of the AF 2.

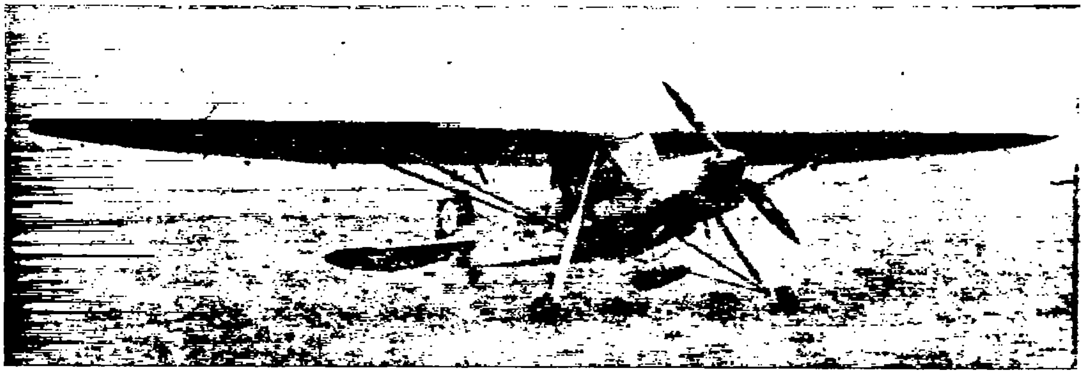


Figure 44.- Airplane with suction, AF 2.

Figure 45.- Airplane with suction, AF 2.

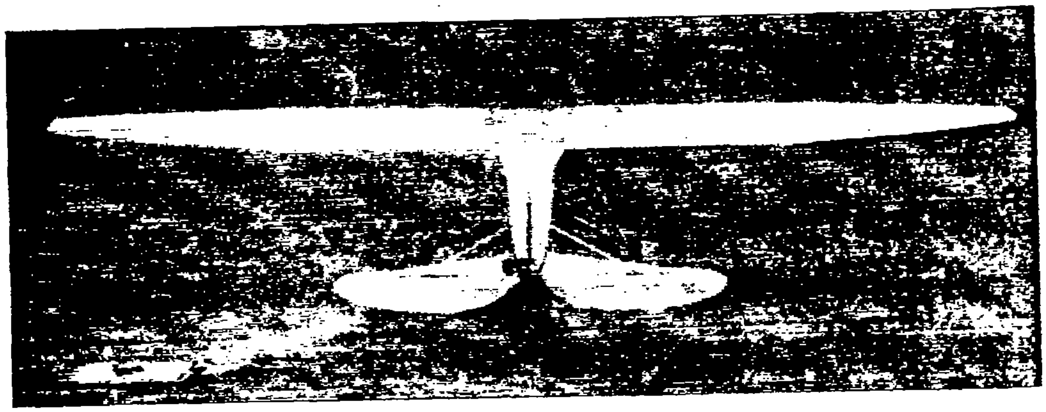


Figure 46.- AF 2, landing flaps retracted.

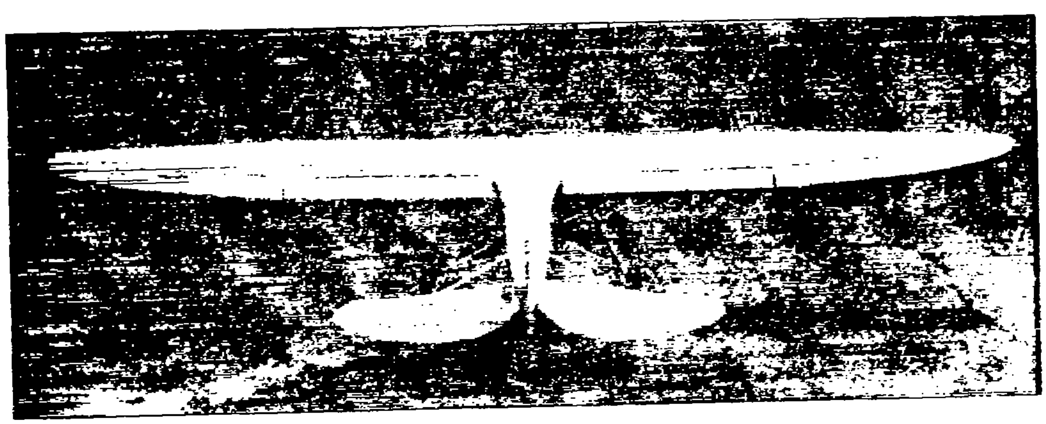


Figure 47.- AF 2, landing flaps deflected.

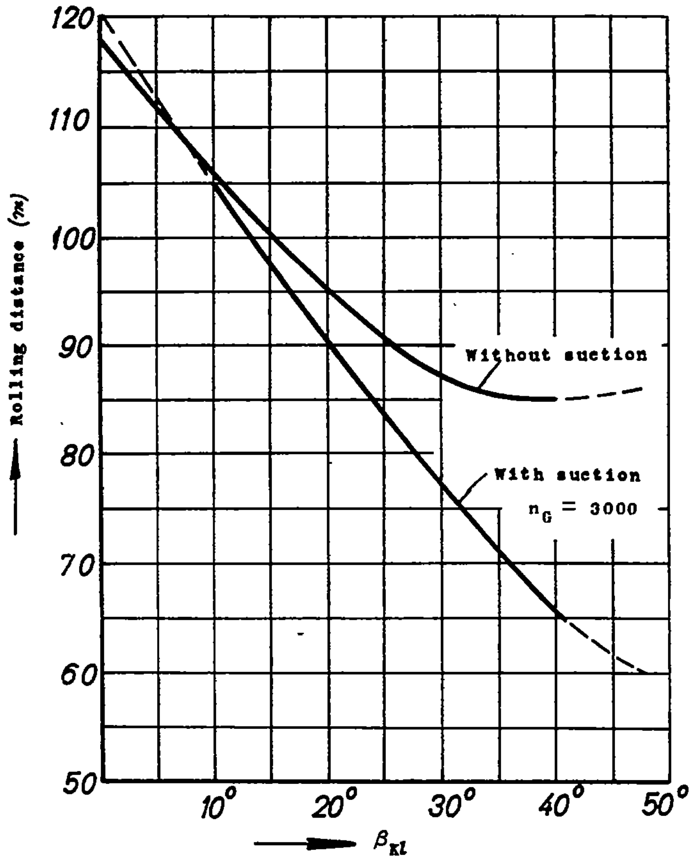


Figure 50.- Rolling distance of the AF 2.

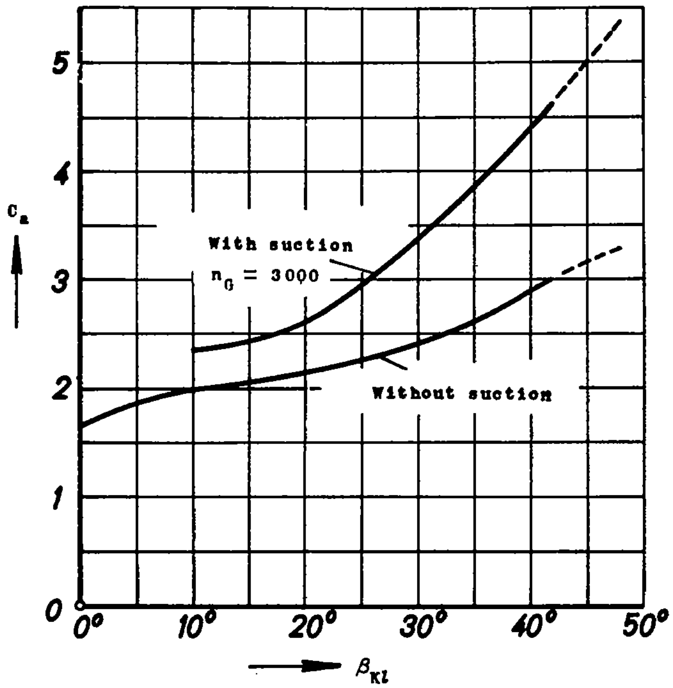


Figure 51.- Lift coefficient for take-off of the AF 2.

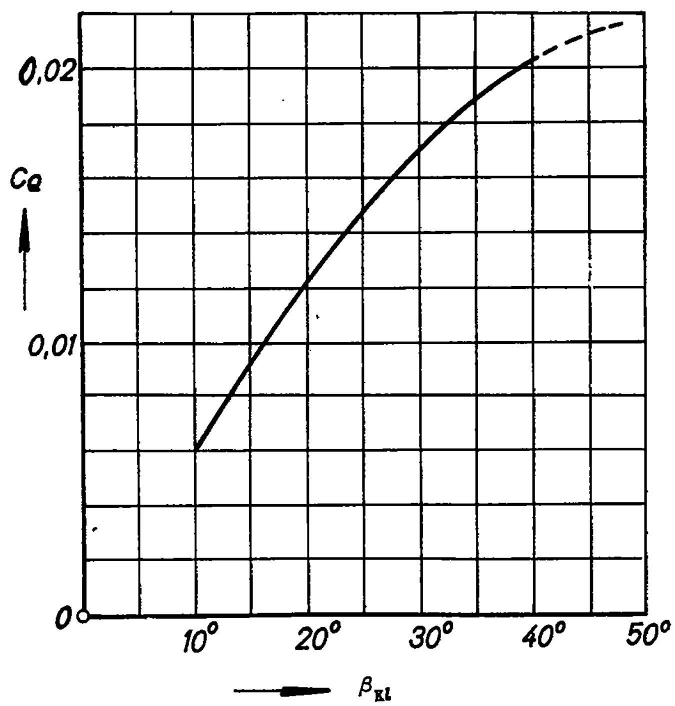


Figure 52.- Quantity coefficient for take-off of the AF 2. n_G = 3000.

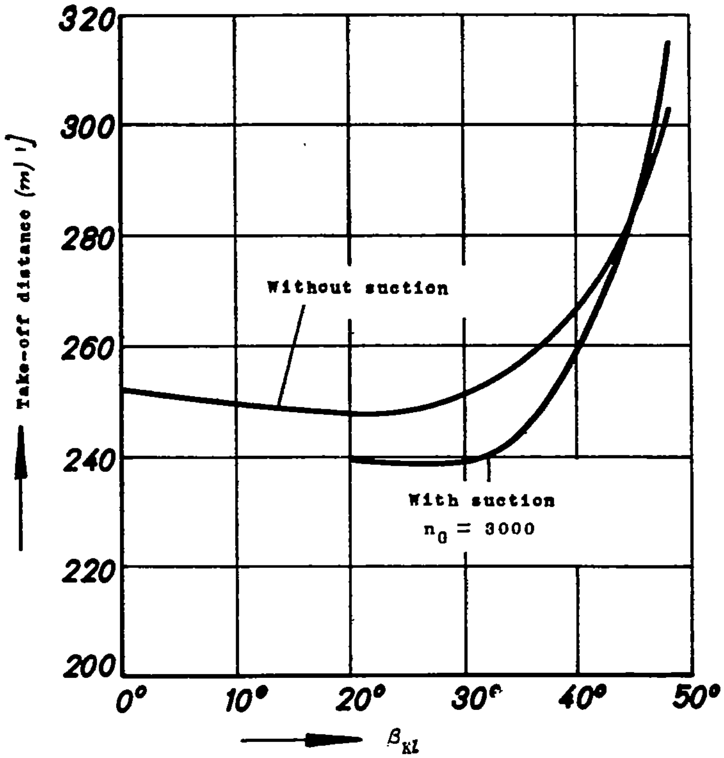


Figure 53.- Take-off distance of the AF 2.

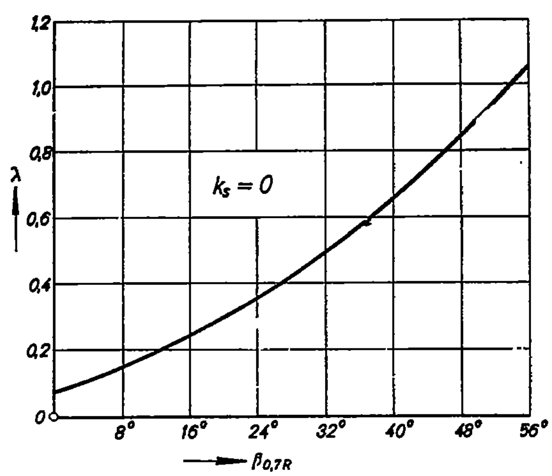


Figure 54.- Advance ratio of the propeller for zero thrust.

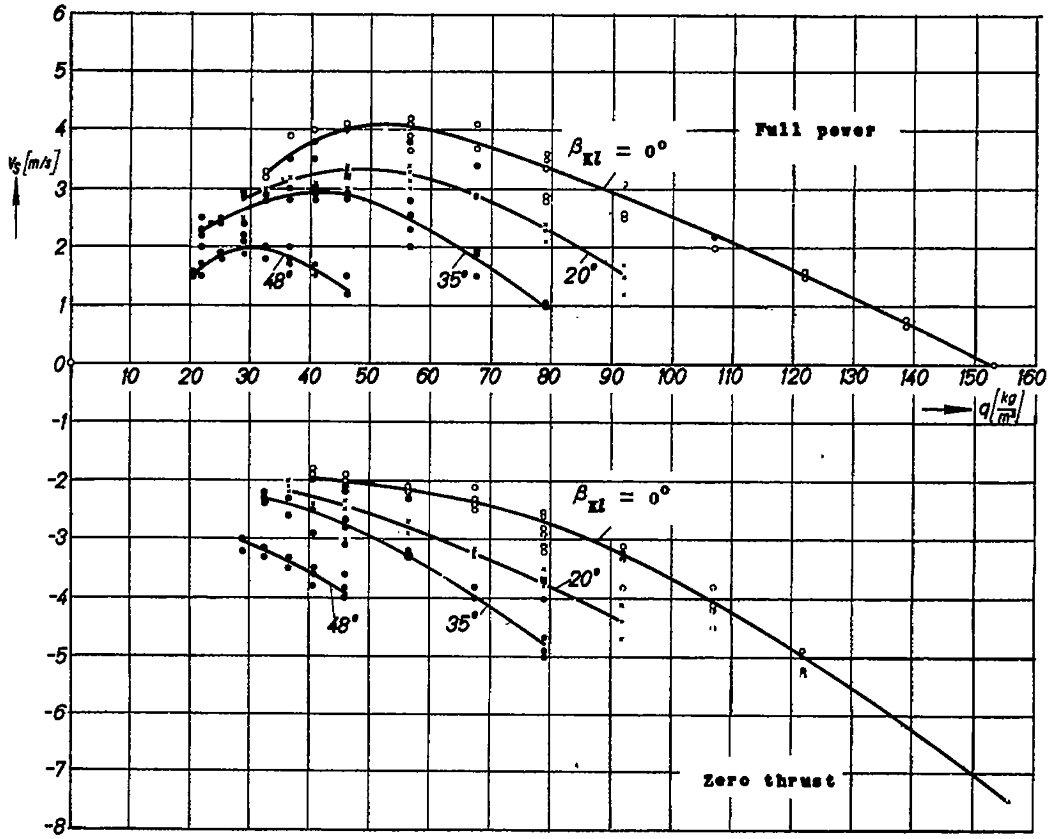


Figure 55.- Rate of climb of the AF 2 without suction.

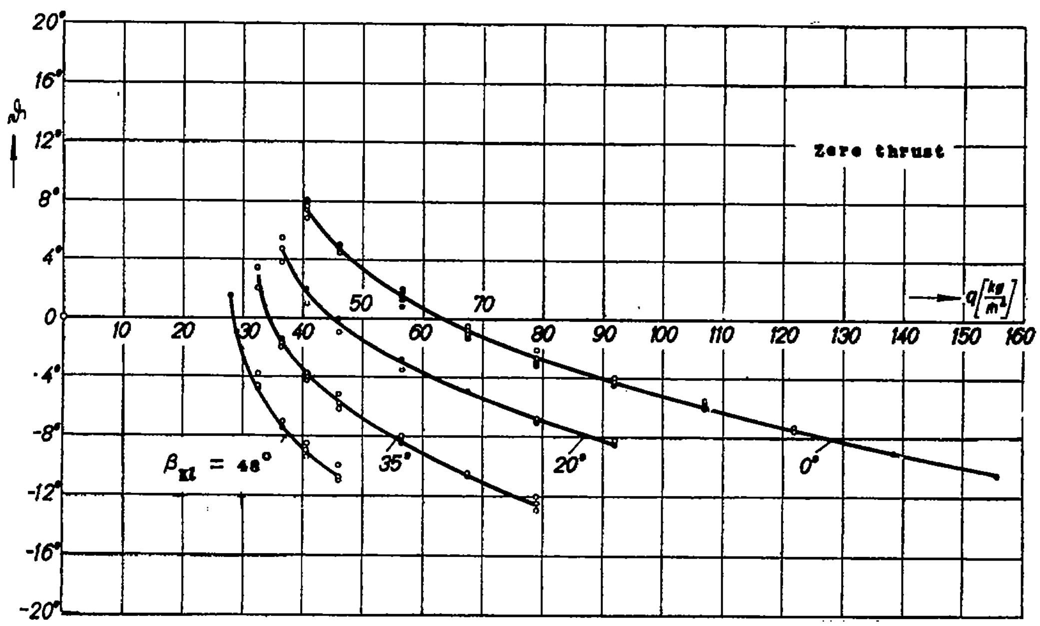


Figure 56.- Pitch of the AF 2 without suction for zero thrust.

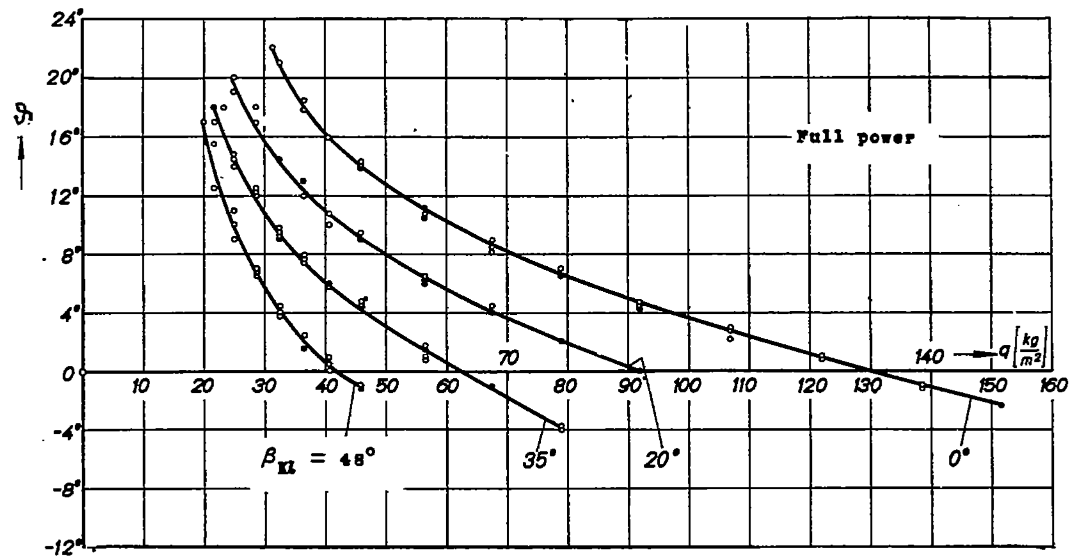


Figure 57.- Pitch of the AF 2 without suction for full power.

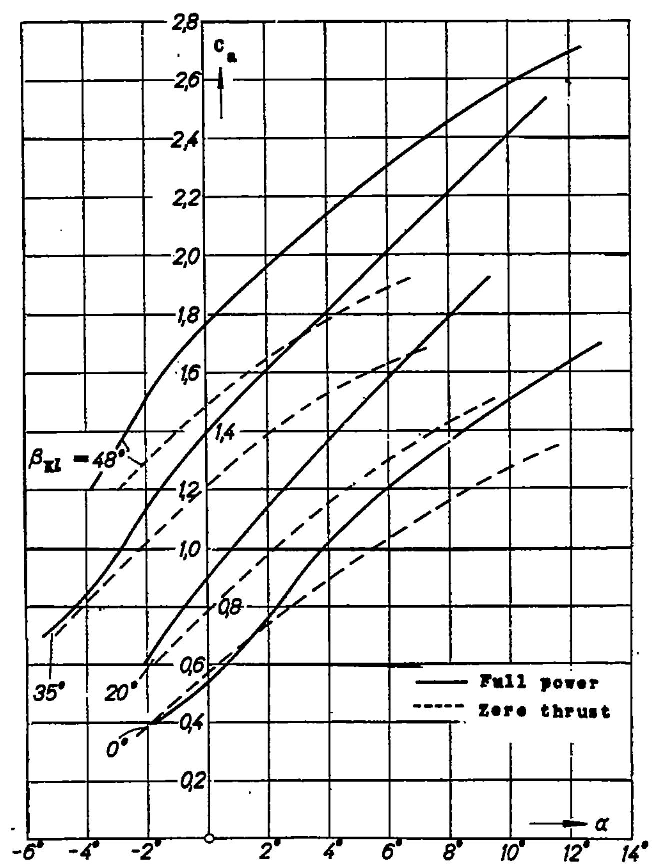


Figure 58.- Lift of the AF 2 without suction.

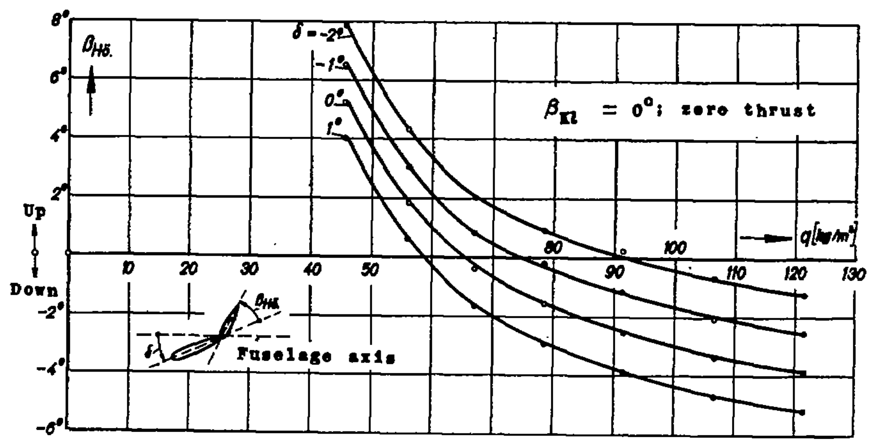


Figure 59.- Relation between stabilizer and elevator deflection of the AF 2.

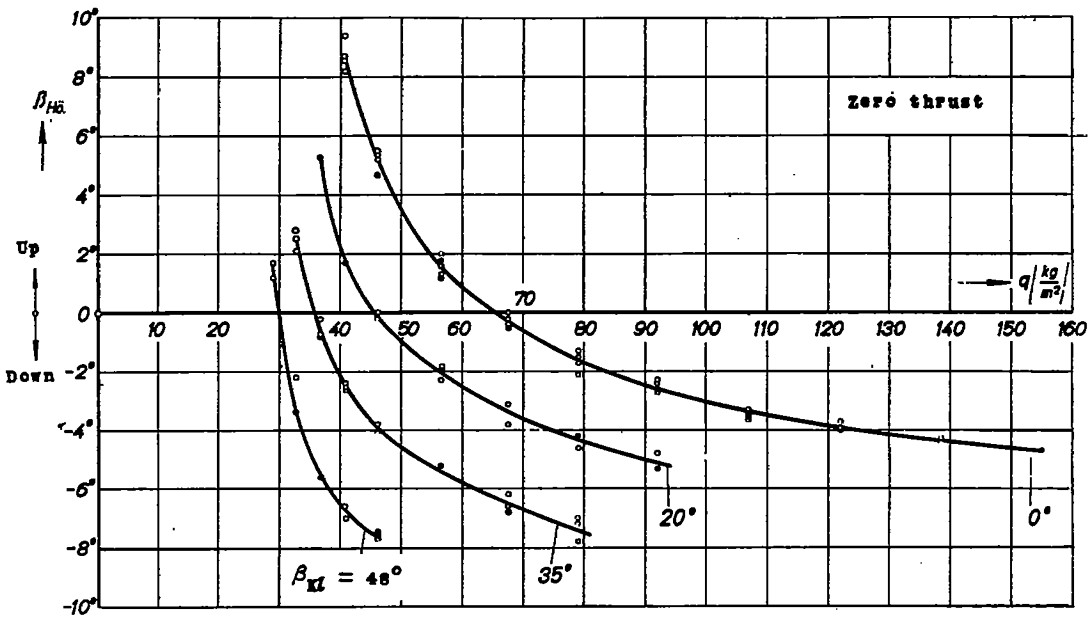


Figure 60.- Elevator deflection of the AF 2 without suction for zero thrust.

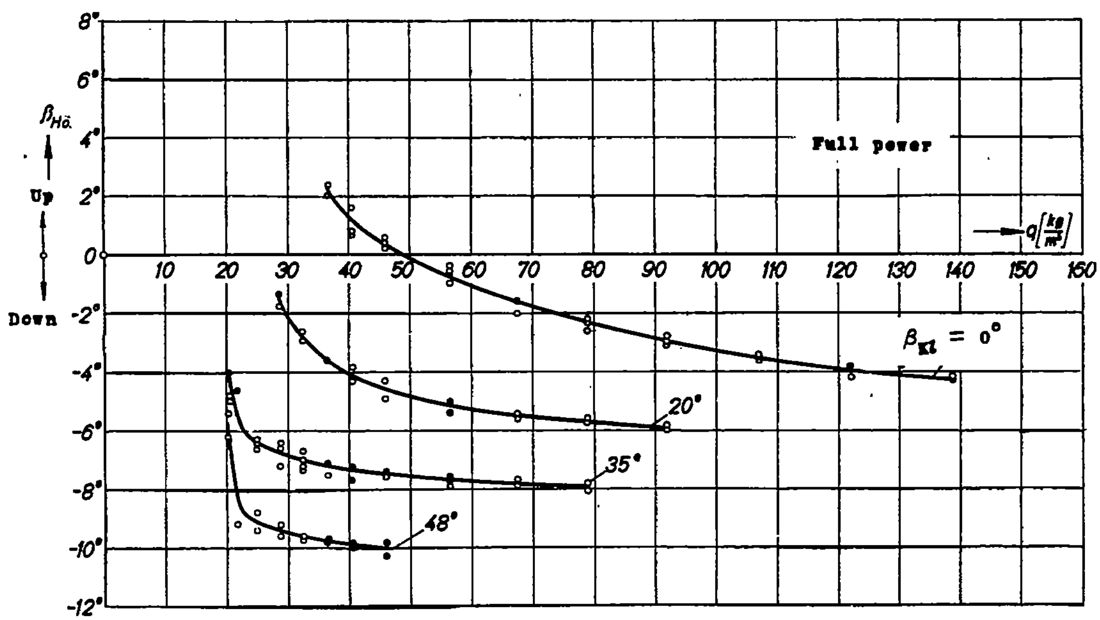


Figure 61.- Elevator deflection of the AF 2 without suction for full power.

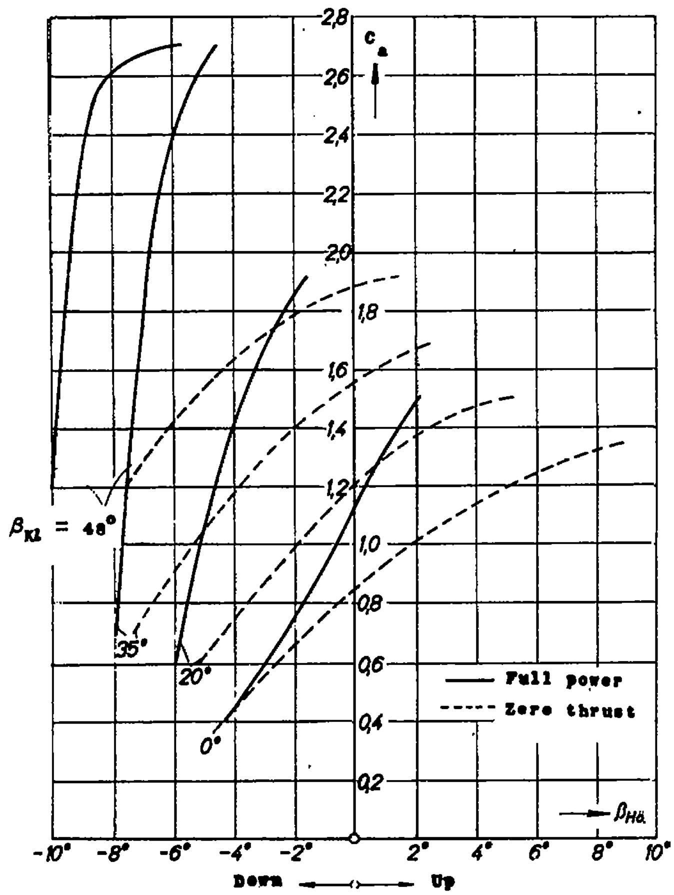


Figure 62.- Lift coefficient of the AF 2 without suction as a function of the elevator deflection.

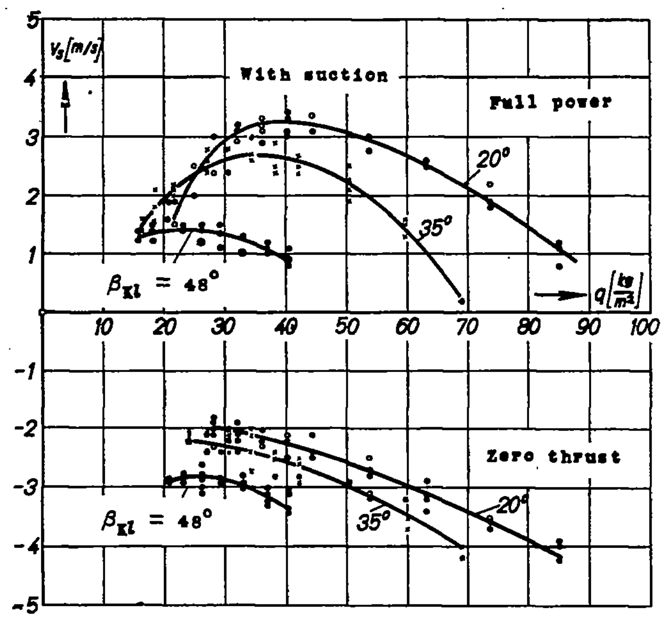


Figure 63.- Rate of climb of the AF 2 with suction, n_G = 3000 rpm.

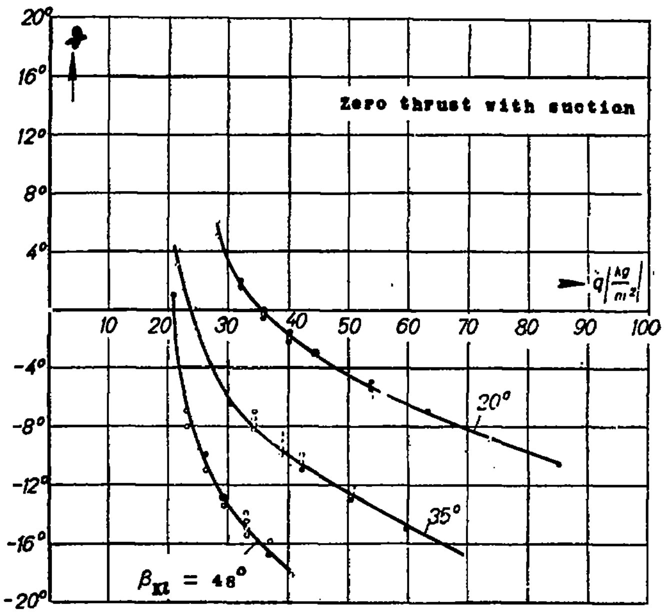


Figure 64.- Pitch of the AF 2 for zero thrust with suction, n_G = 3000 rpm.

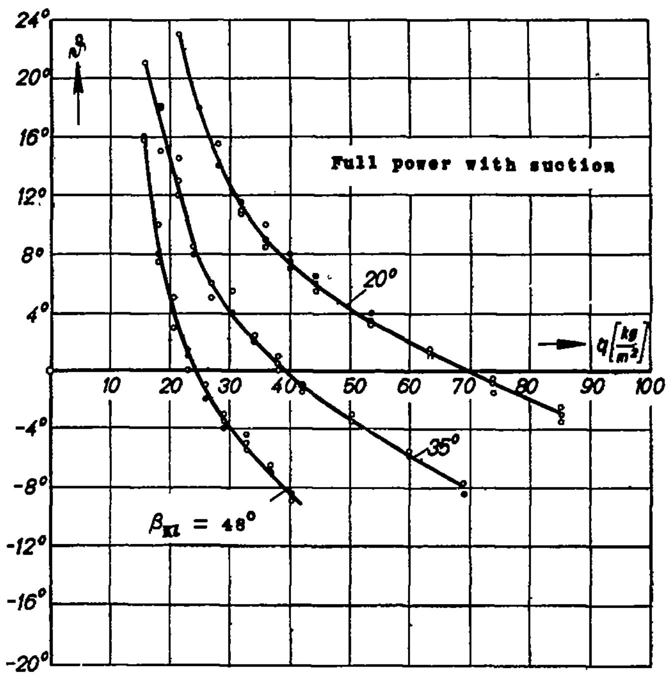


Figure 65.- Pitch of the AF 2 for full power with suction, n_G = 3000 rpm.

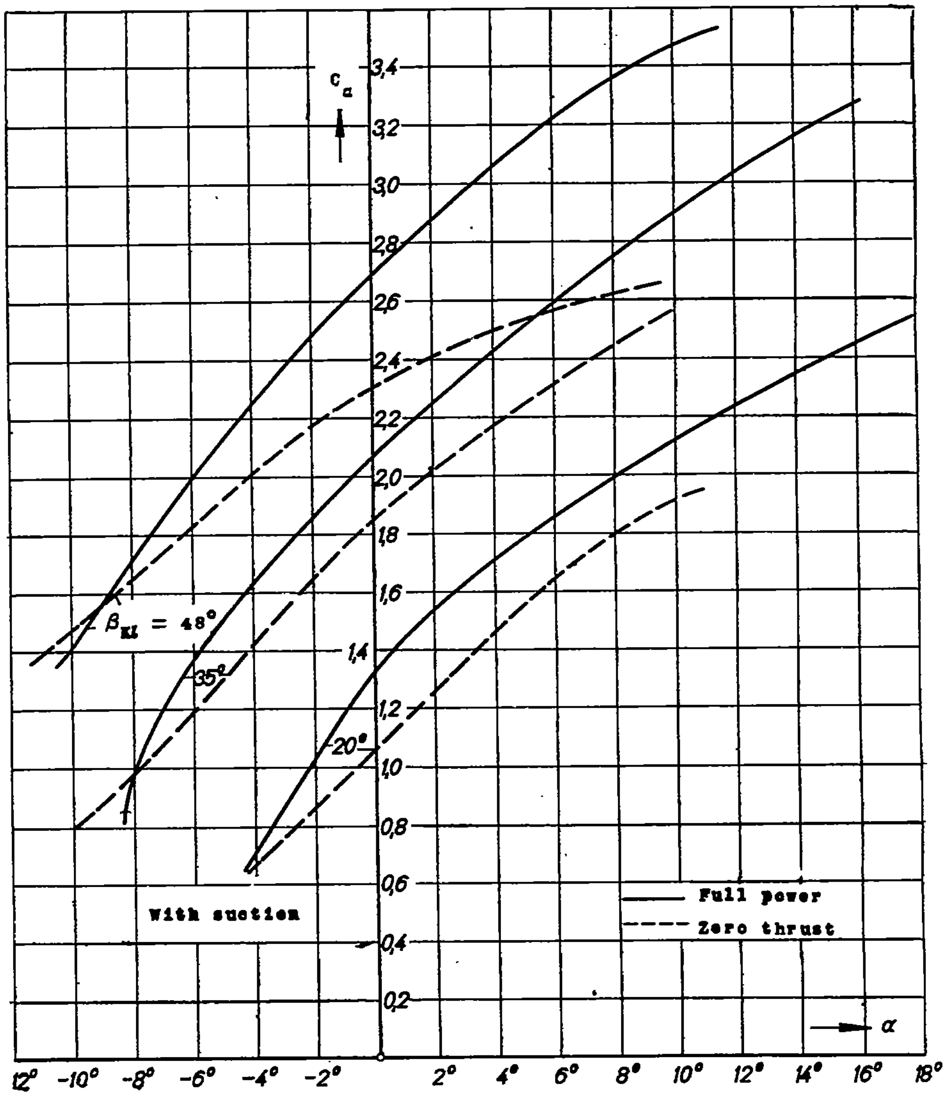


Figure 66.- Lift coefficients of the AF 2 with suction, n_G = 3000 rpm.

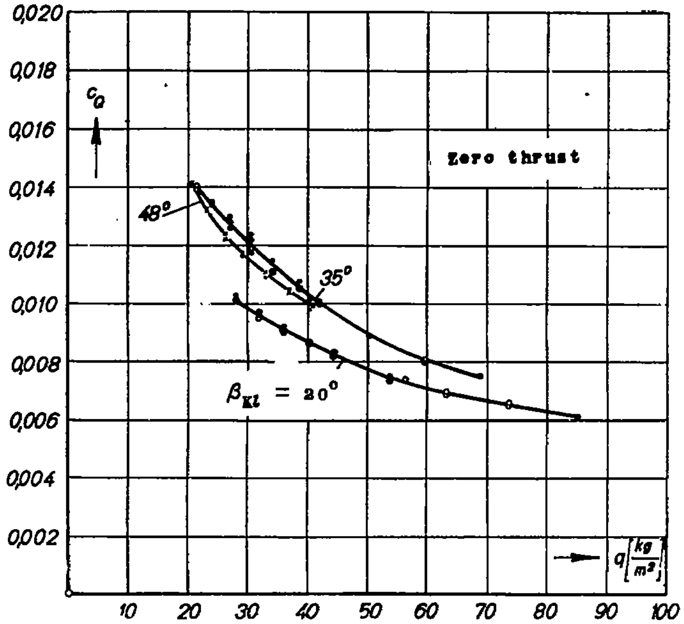


Figure 67.- Suction quantity of the AF 2 for zero thrust, n_G = 3000 rpm.

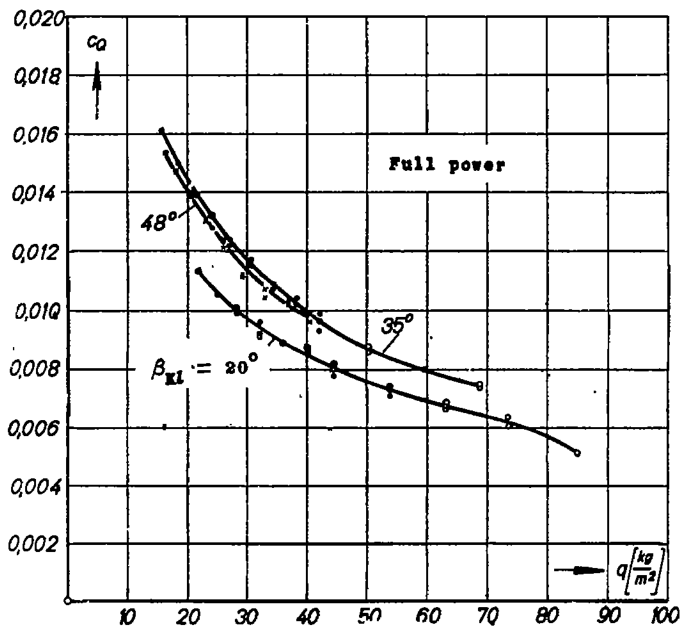


Figure 68.- Suction quantity of the AF 2 for full power, n_G = 3000 rpm.

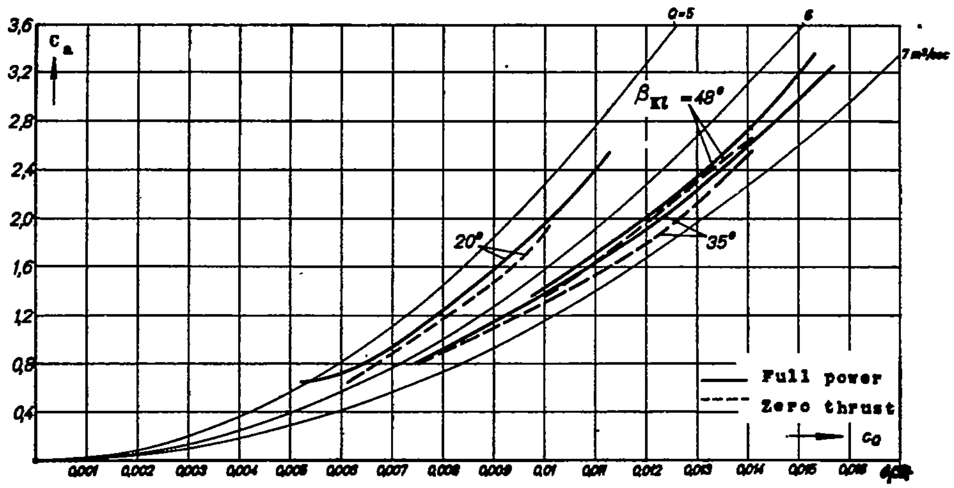


Figure 69.- Lift coefficient of the AF 2 as a function of the quantity coefficient, n_G = 3000 rpm.

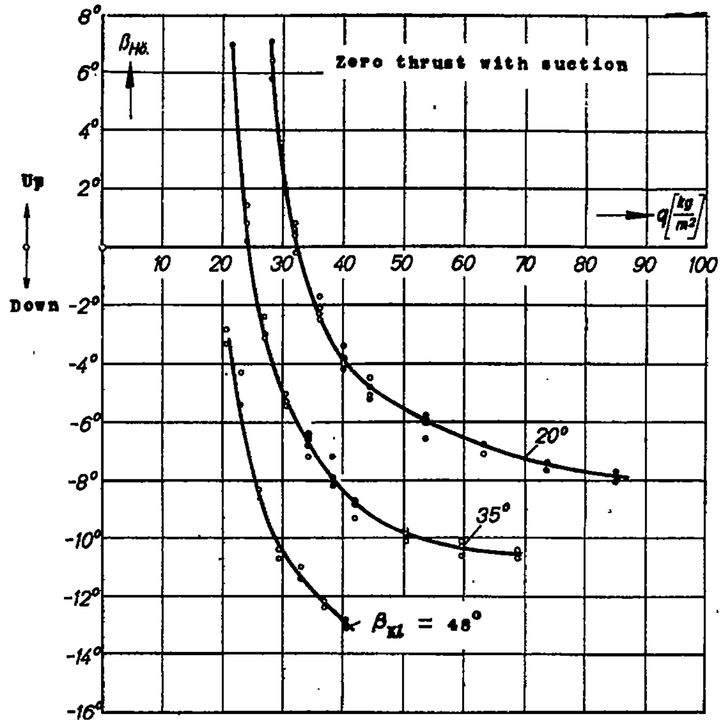


Figure 70.- Elevator deflection of the AF 2 for zero thrust with suction, n_G = 3000 rpm.

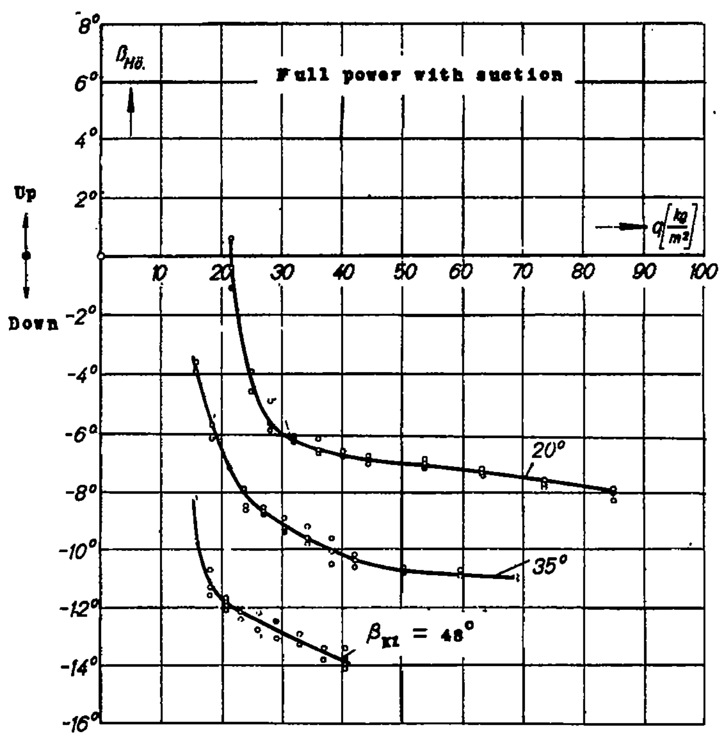


Figure 71.- Elevator deflection of the AF 2 for full power with suction, n_G = 3000 rpm.

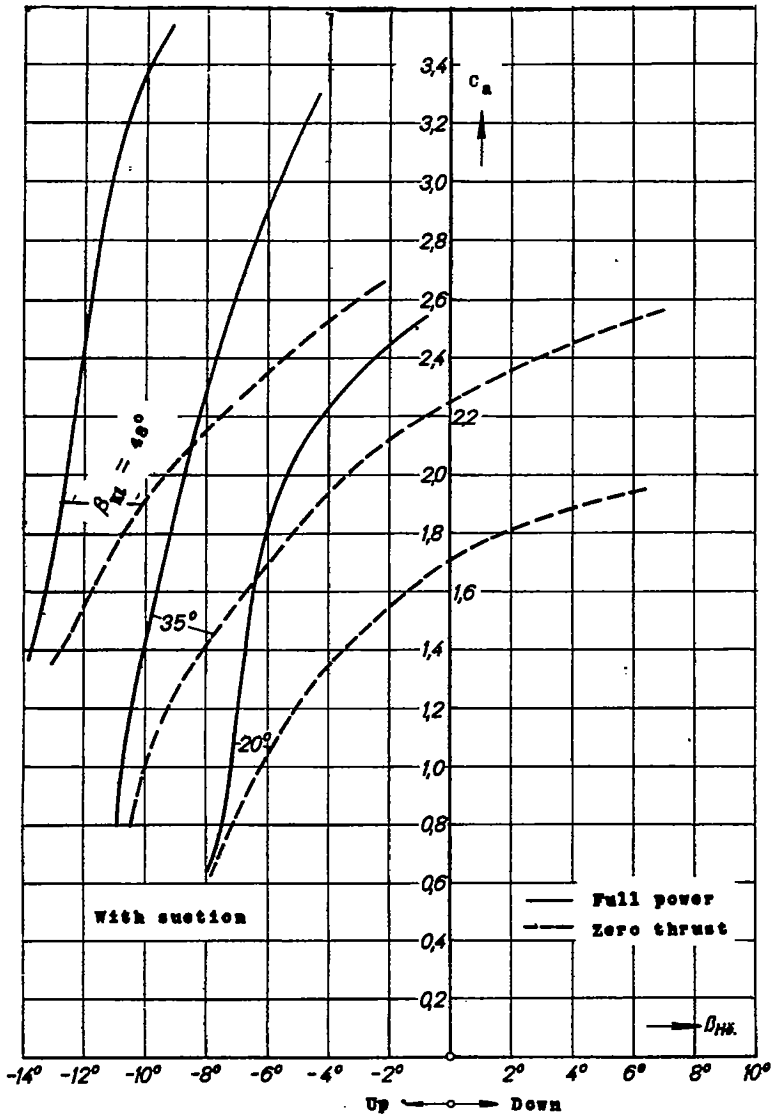


Figure 72.- Lift of the AF 2 as a function of the elevator deflection in case of suction, n_G = 3000 rpm.

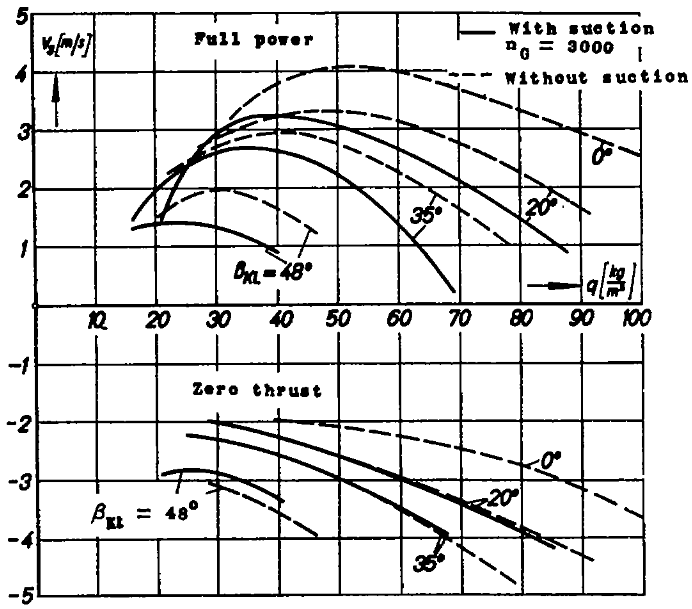


Figure 73.- Rate of climb of the AF 2.

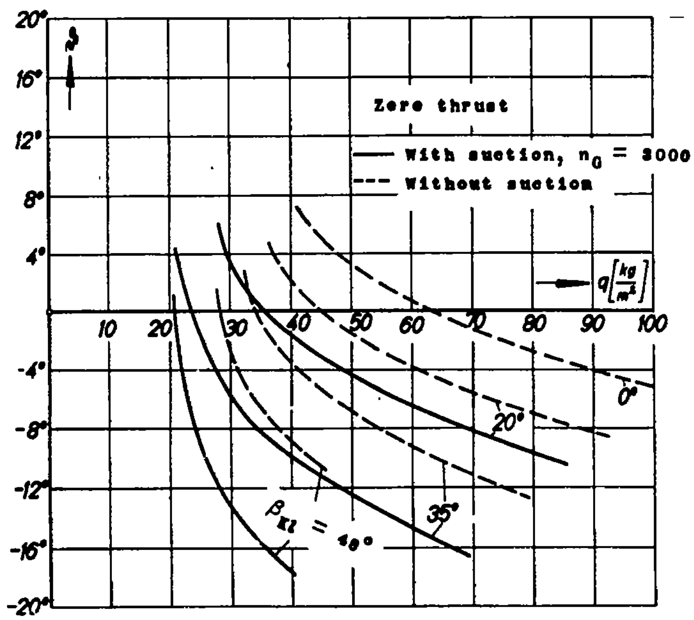


Figure 74.- Pitch of the AF 2 for zero thrust.

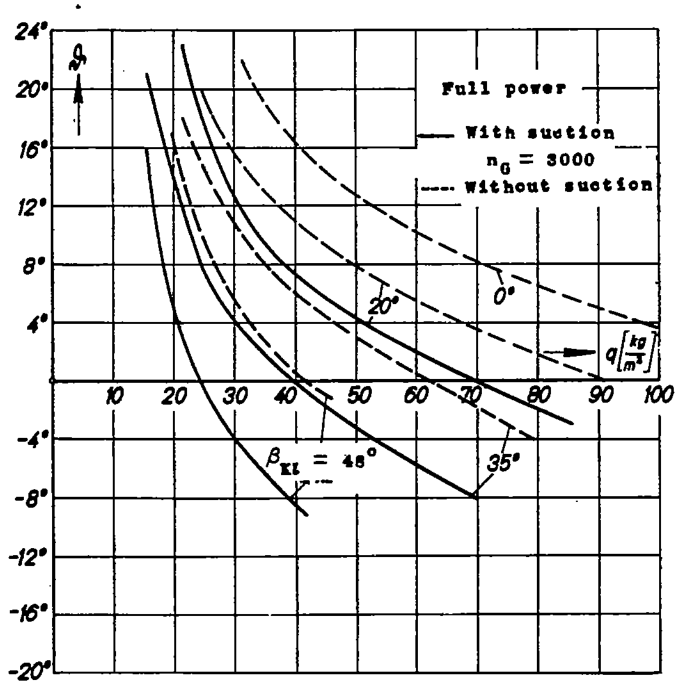


Figure 75.- Pitch of the AF 2 for full power.

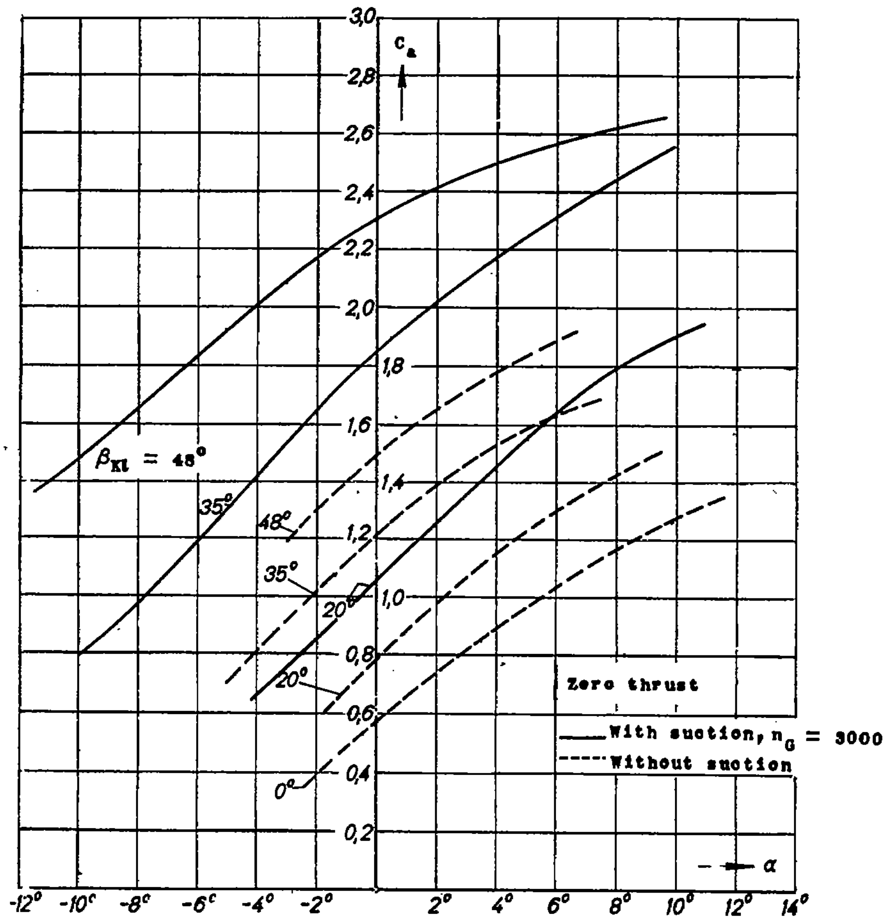


Figure 76.- Lift of the AF 2 for zero thrust.

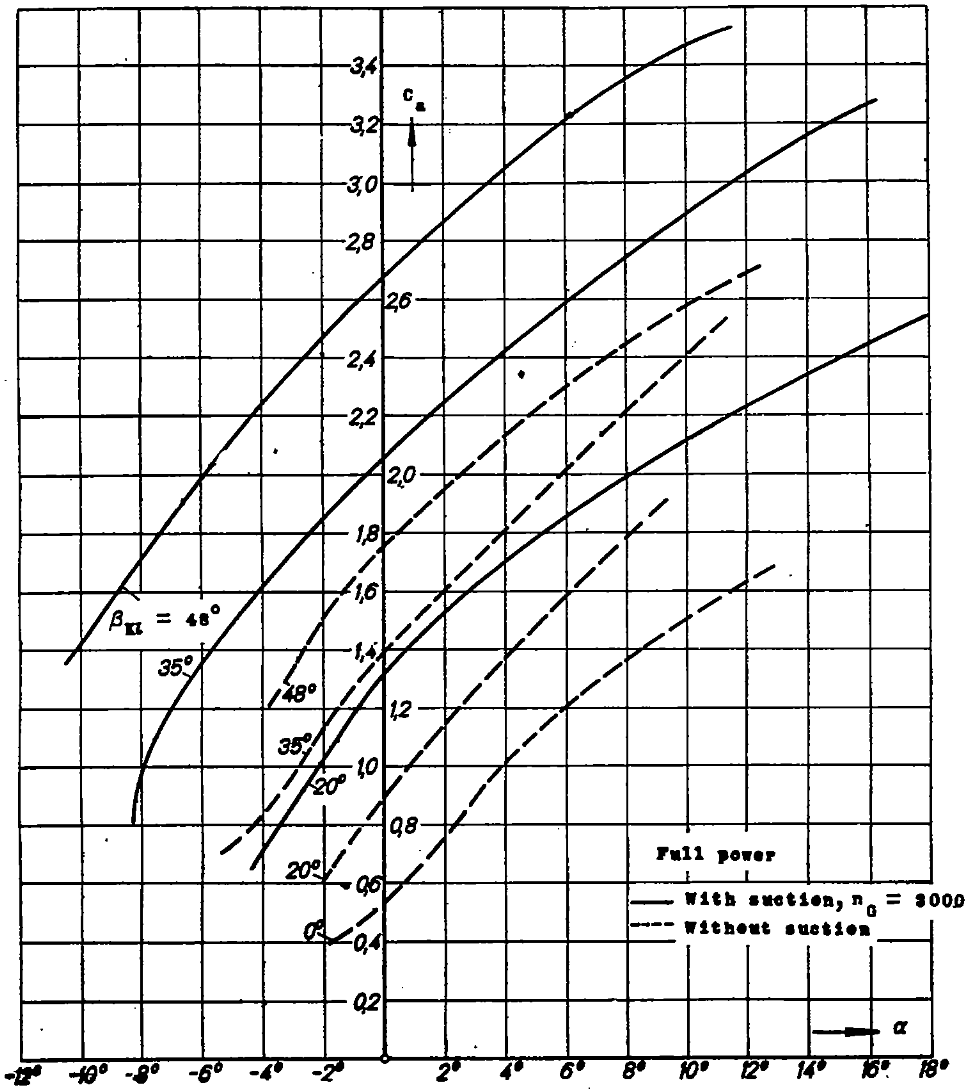


Figure 77.- Lift of the AF 2 for full power.

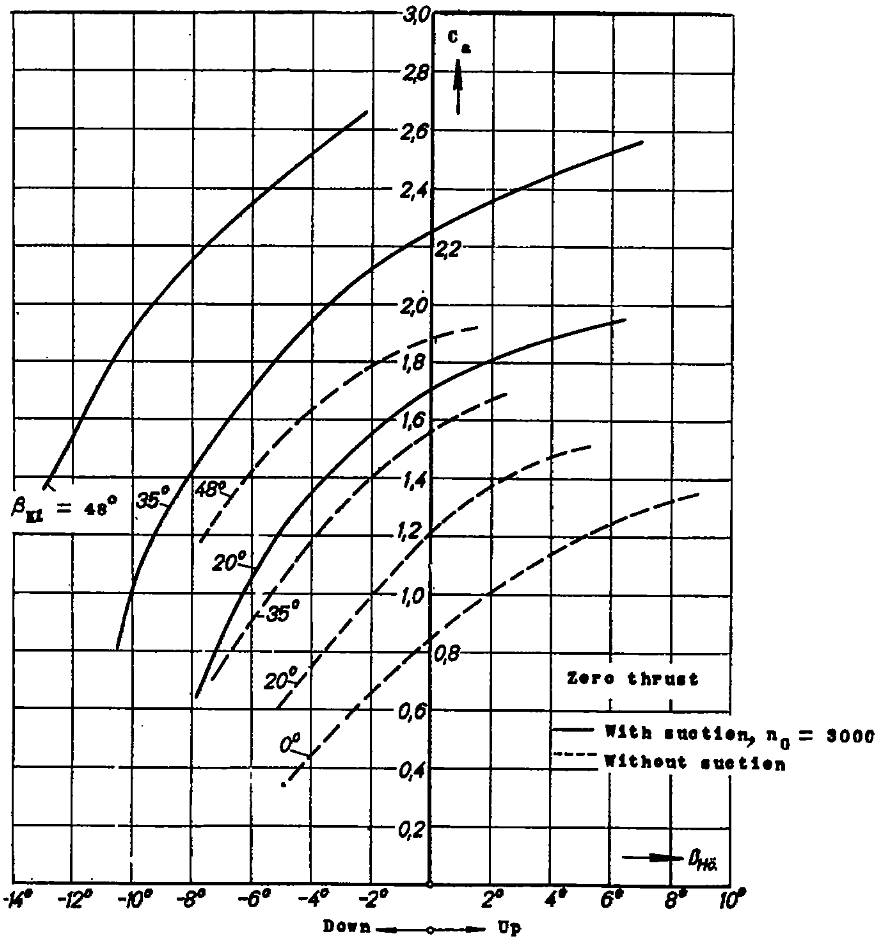


Figure 78.- Lift of the AF 2 as a function of the elevator deflection for zero thrust.

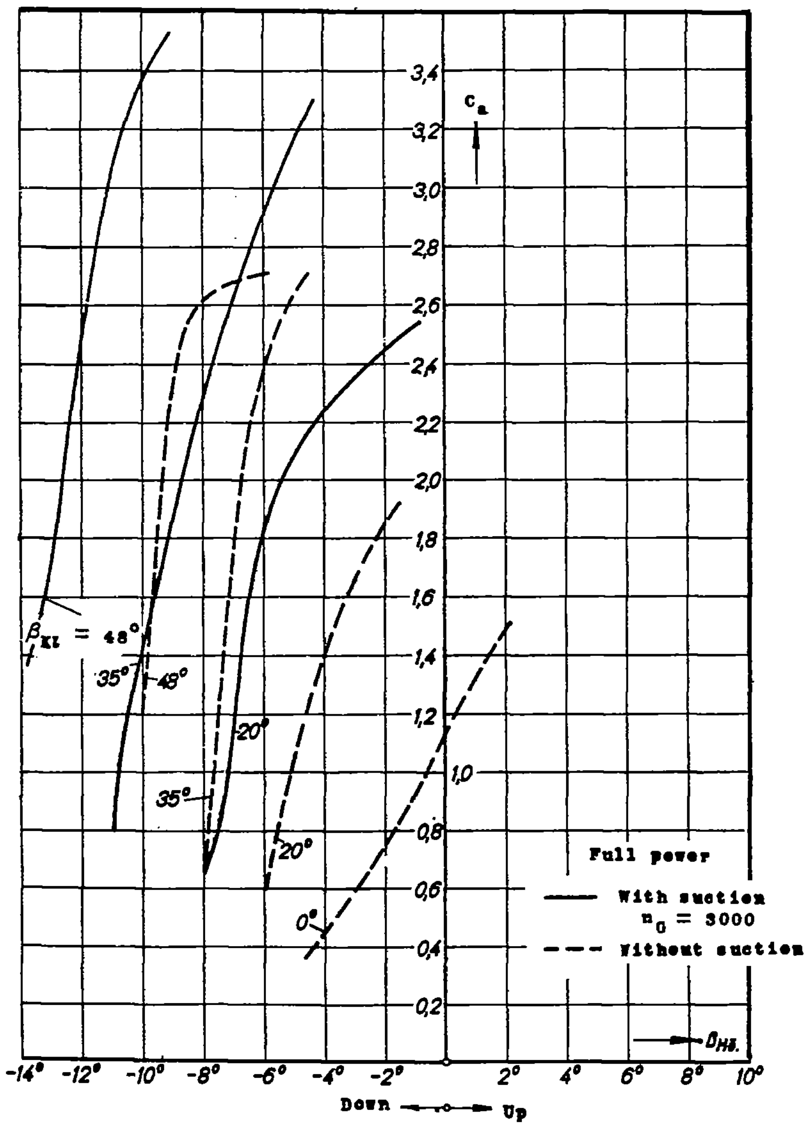


Figure 79.- Lift of the AF 2 as a function of the elevator deflection for full power.

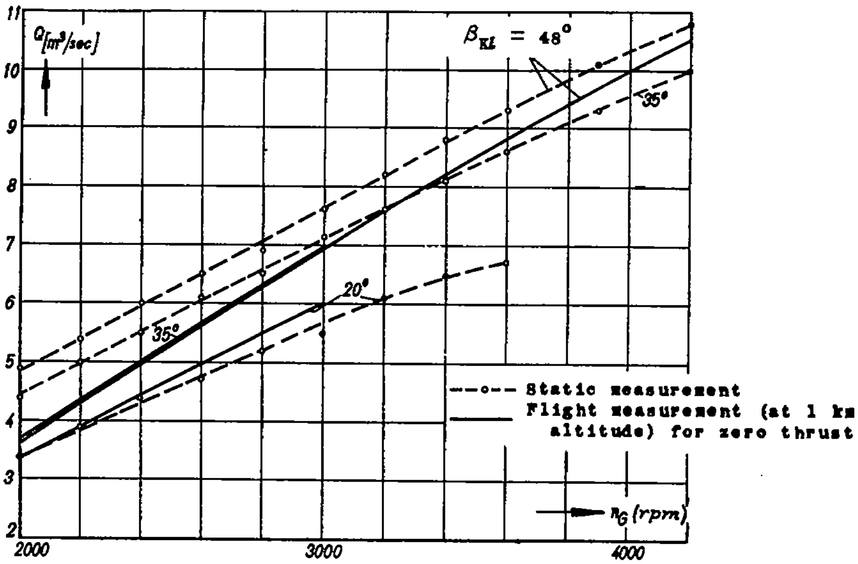


Figure 80.- Suction quantity of the AF 2 for various blower rpm.

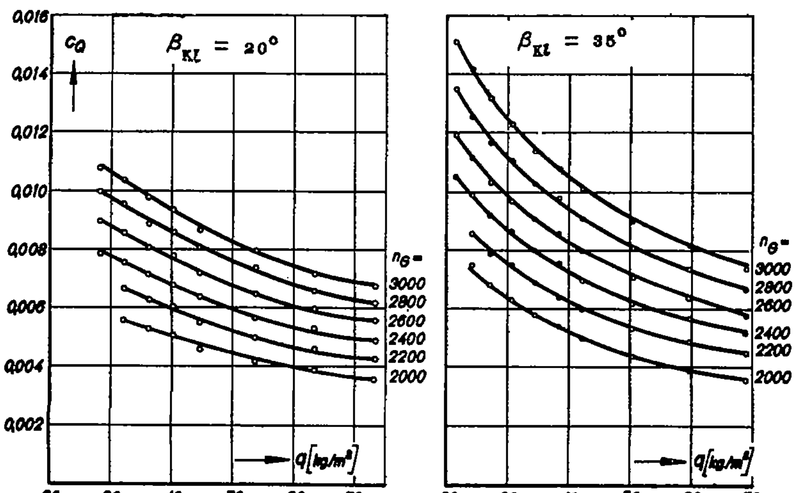


Figure 81.- Quantity coefficient of the AF 2, $\beta_{Kl} = 20^{\circ}$ and 35°, zero thrust.

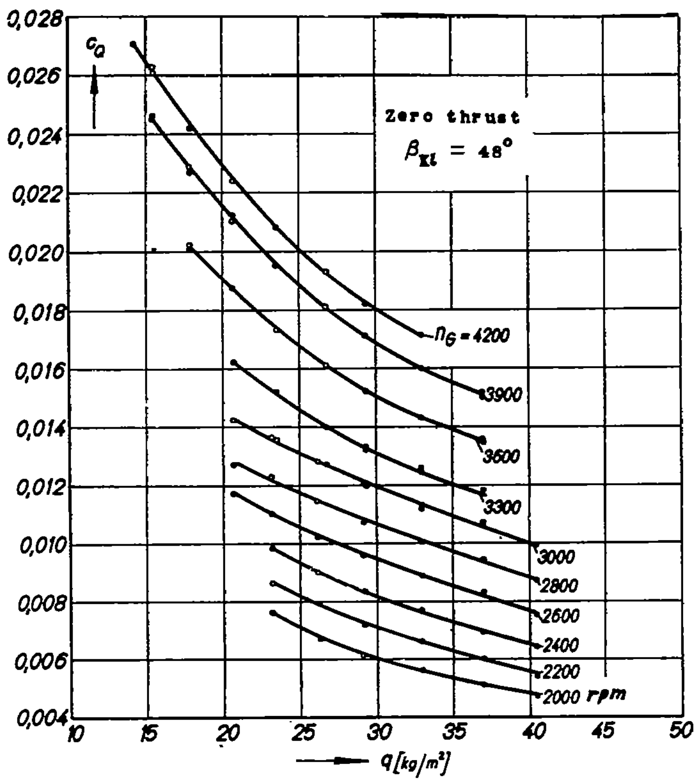


Figure 82.- Quantity coefficient of the AF 2, β_{Kl} = 48°, zero thrust.

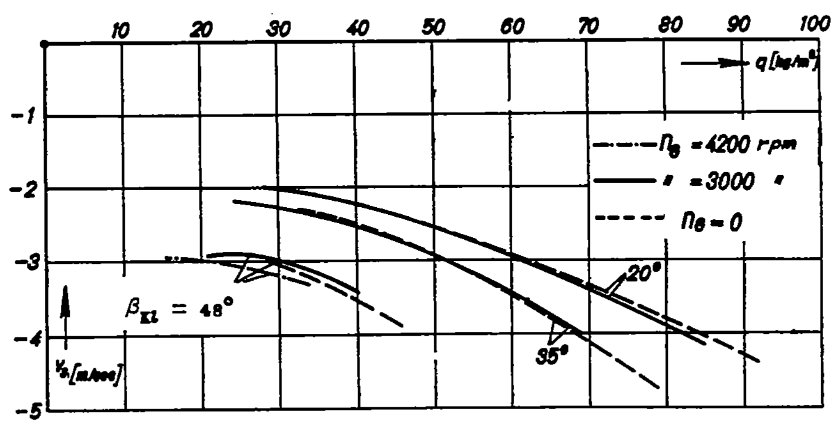


Figure 83.- Rate of climb of the AF 2 for zero thrust.

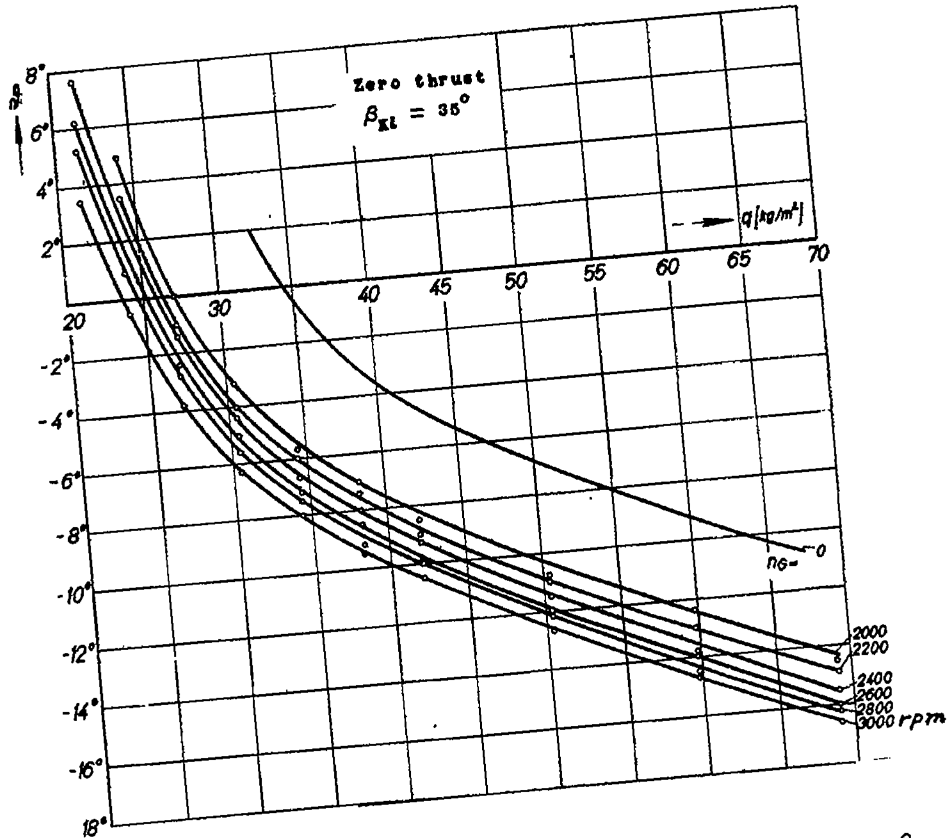


Figure 84.- Pitch of the AF 2 for various suction quantities, $\beta_{Kl} = 35^{\circ}$, zero thrust.

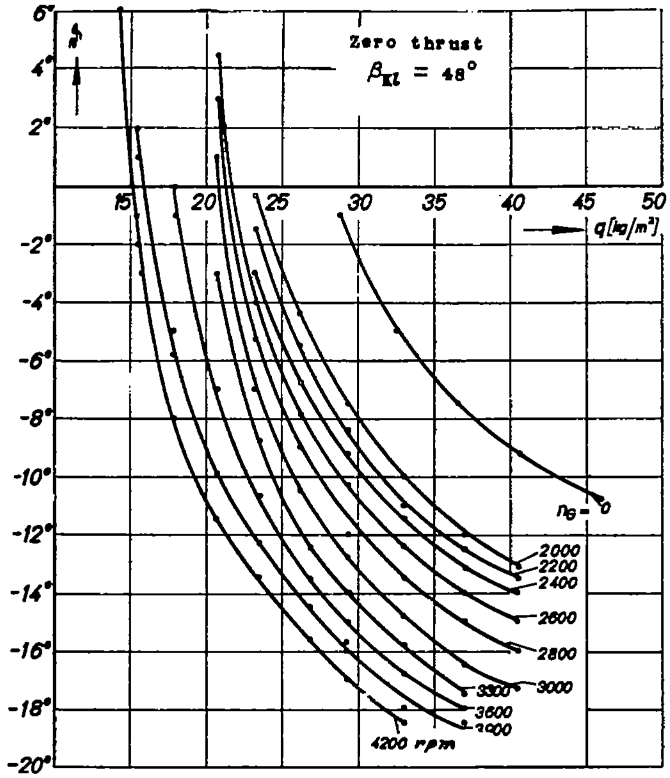


Figure 85.- Pitch of the AF 2 for various suction quantities, β_{Kl} = 48°, zero thrust.

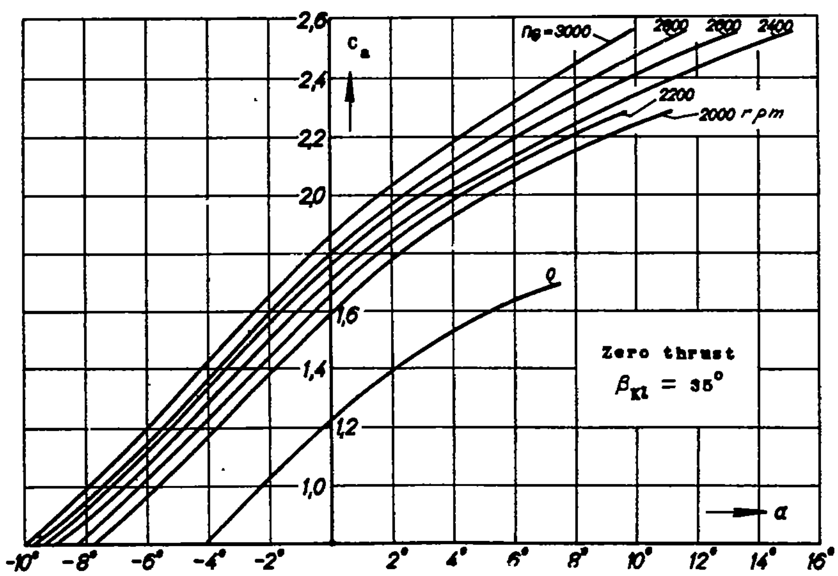


Figure 86.- Lift of the AF 2 for various suction quantities, β_{Kl} = 35°, zero thrust.

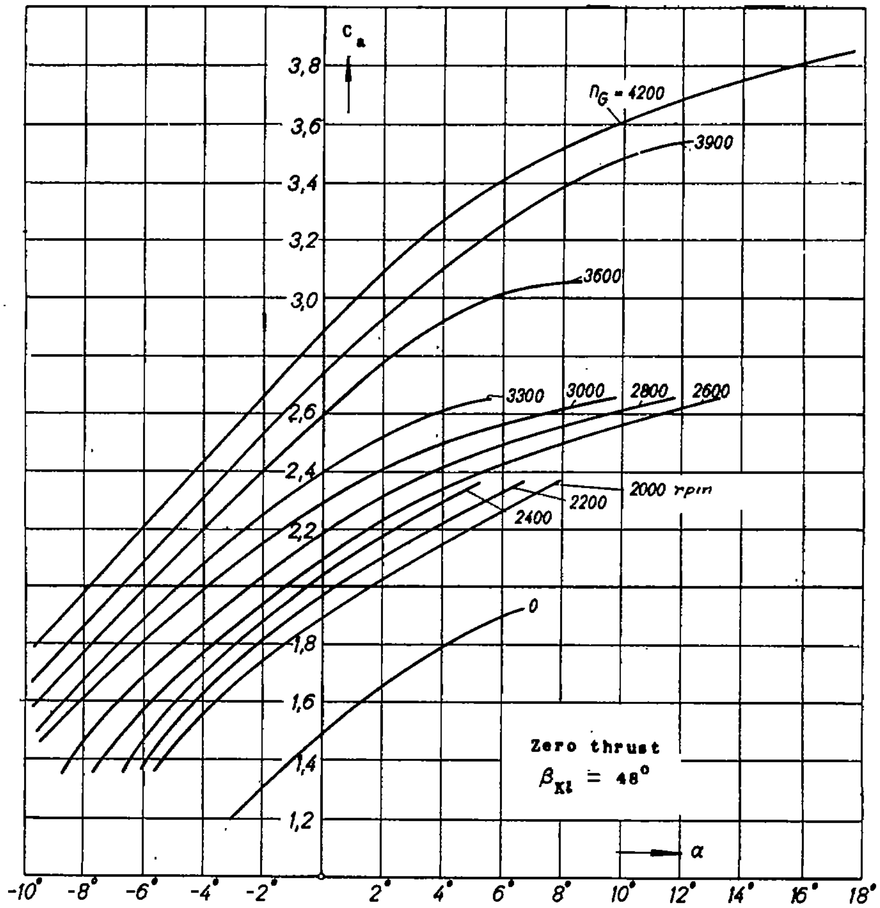


Figure 87.- Lift of the AF 2 for various suction quantities, $\beta_{Kl} = 48^{\circ}$, zero thrust.

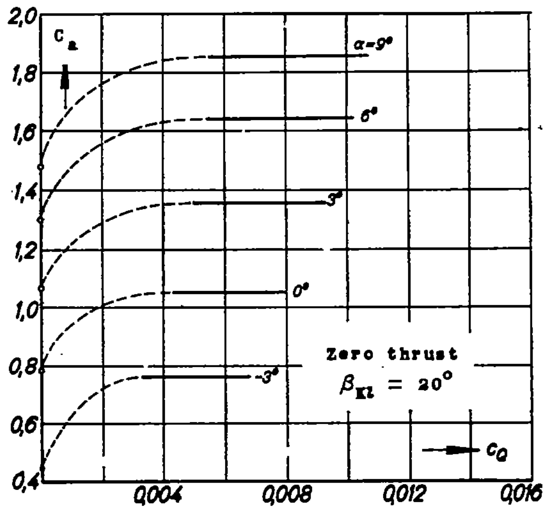


Figure 88.- Lift of the AF 2 as a function of the suction quantity, $\beta_{Kl} = 20^{\circ}$, zero thrust.

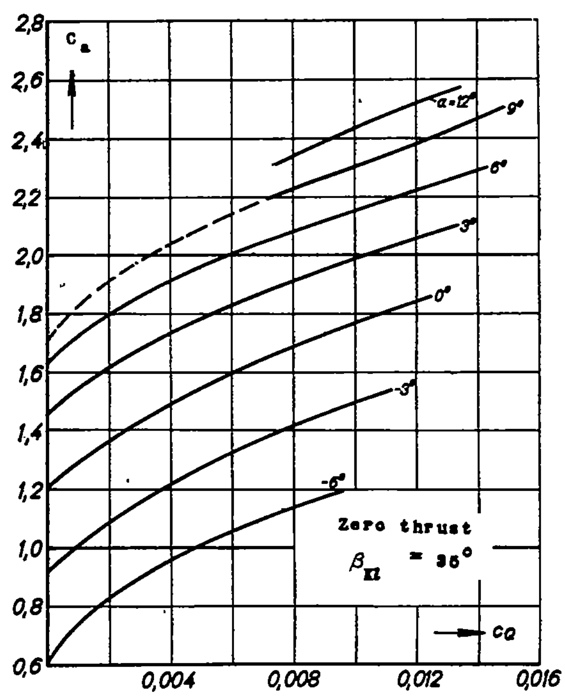


Figure 89.- Lift of the AF 2 as a function of the suction quantity, $\beta_{Kl} = 35^{\circ}$, zero thrust.

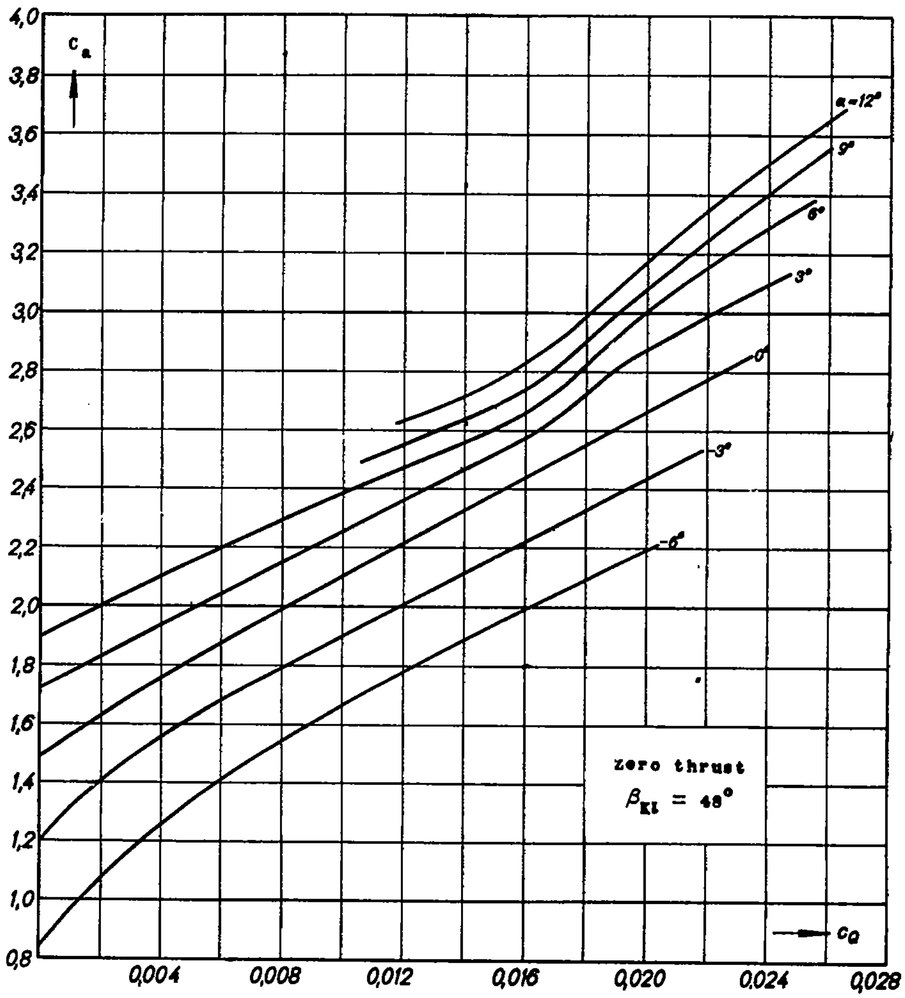


Figure 90.- Lift of the AF 2 as a function of the suction quantity, $\beta_{Kl} = 48^{\circ}$, zero thrust.

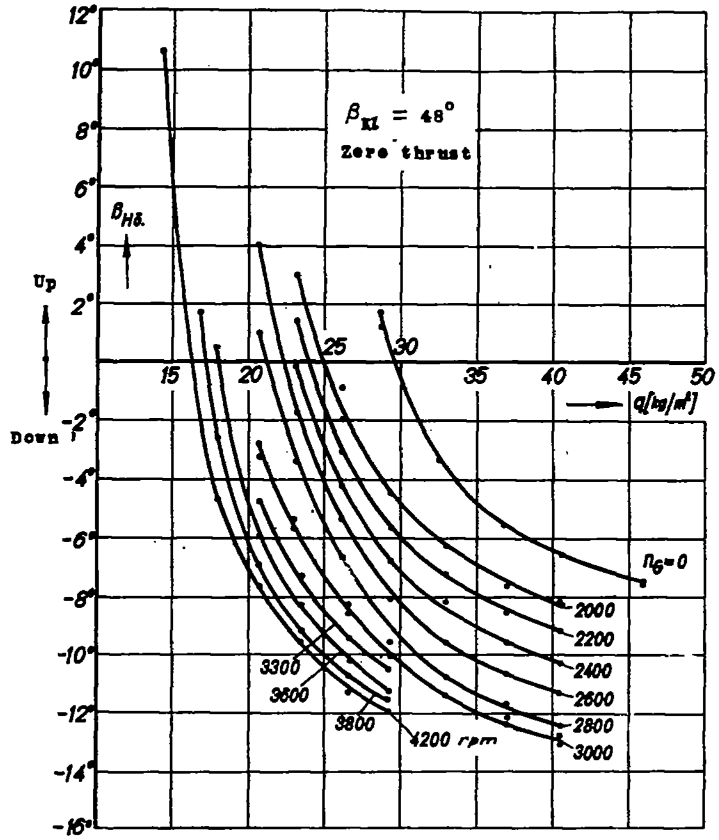


Figure 91.- Elevator deflection of the AF 2 for various suction quantities, β_{Kl} = 48°, zero thrust.

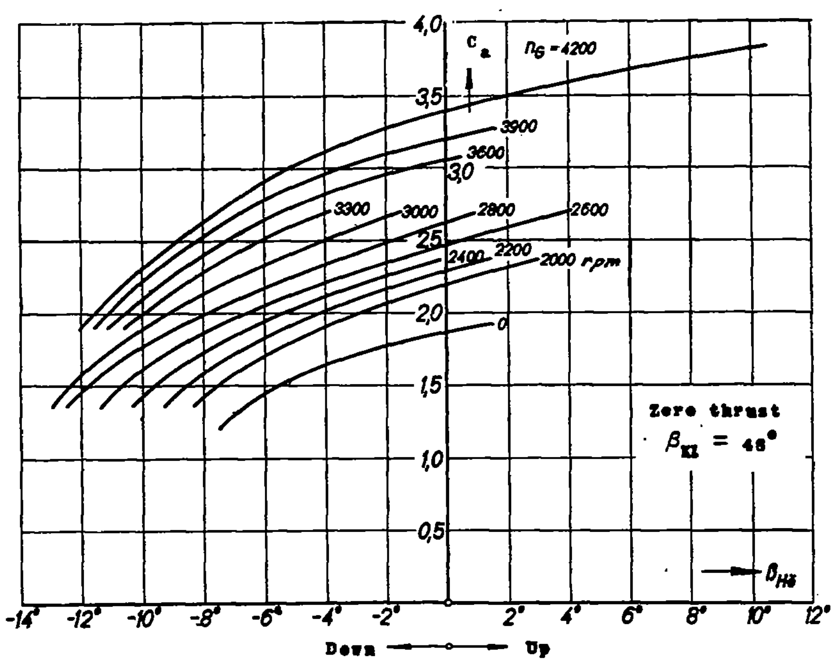


Figure 92.- Lift of the AF 2 as a function of the elevator deflection for various suction quantities, β_{Kl} = 48°, zero thrust.

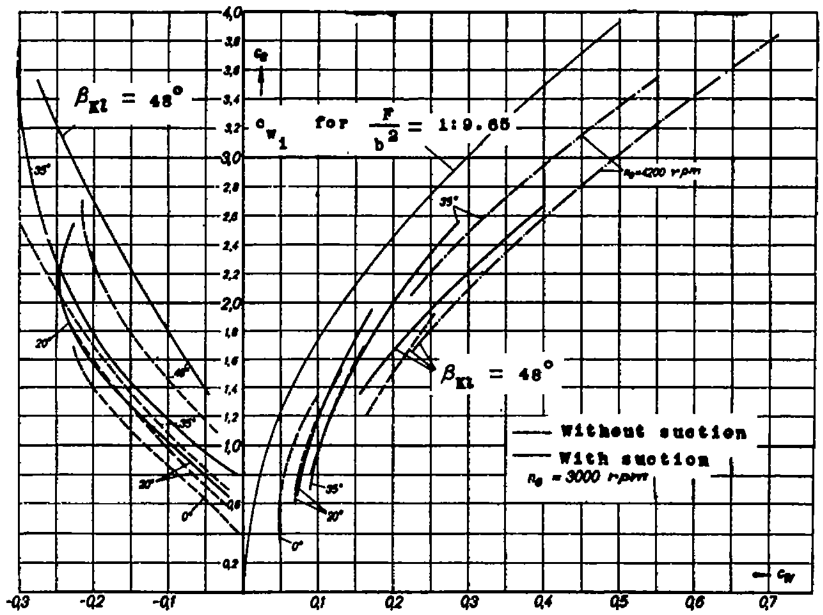


Figure 93.- Polars of the AF 2.

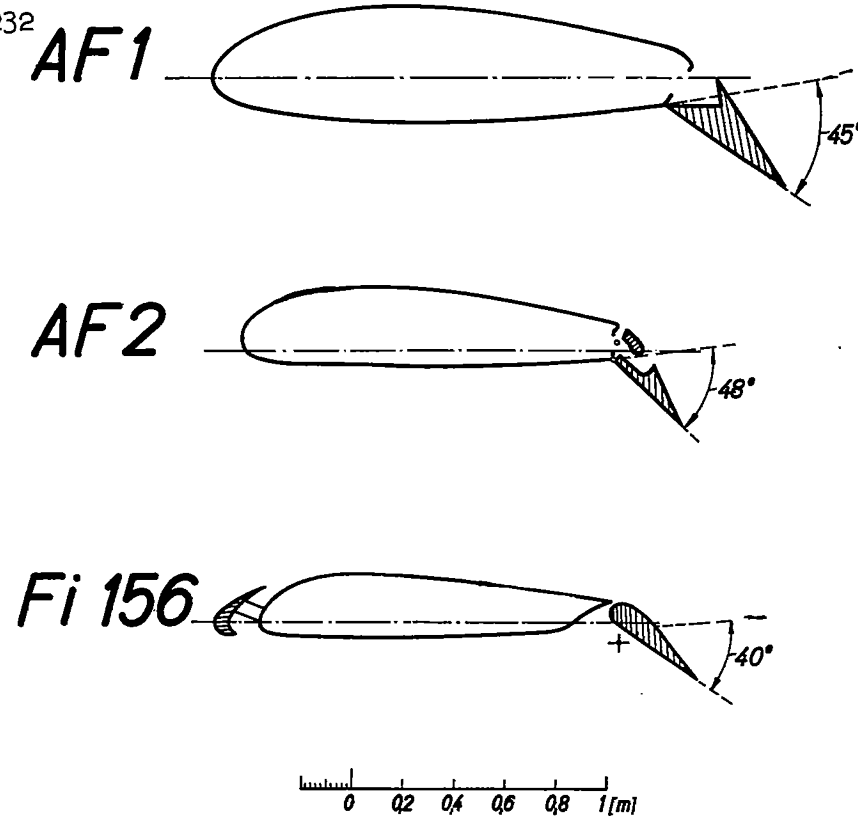


Figure 94.- Profiles of the AF 1, AF 2, and Fi 156 near fuselage.

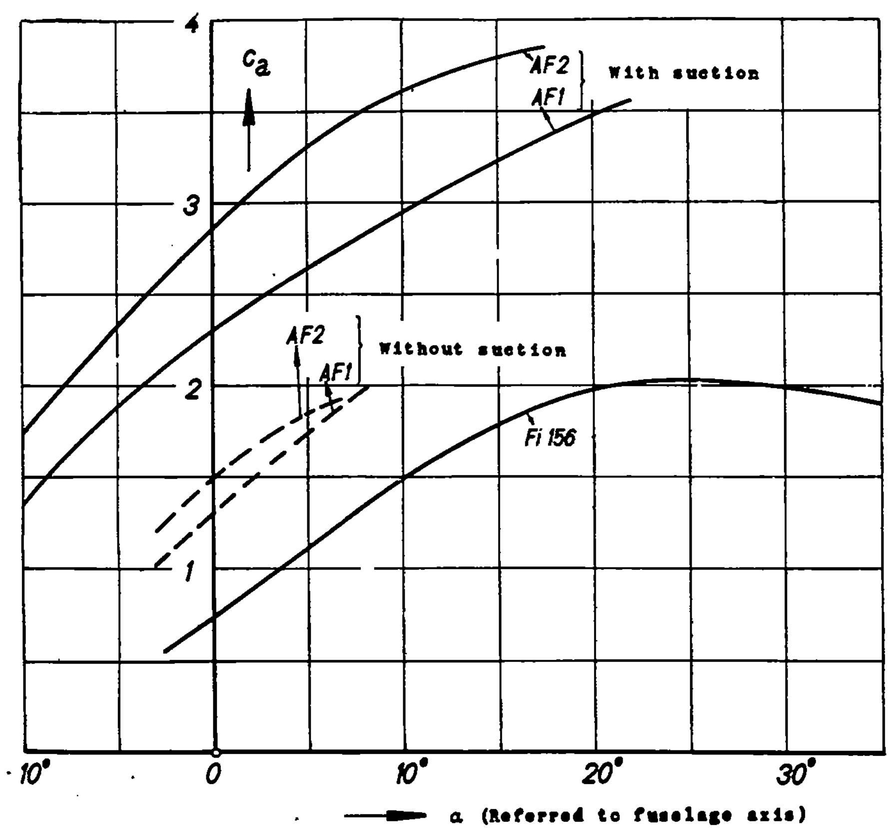


Figure 95.- Lift for power off and zero thrust, respectively, for full landing-flap deflection.

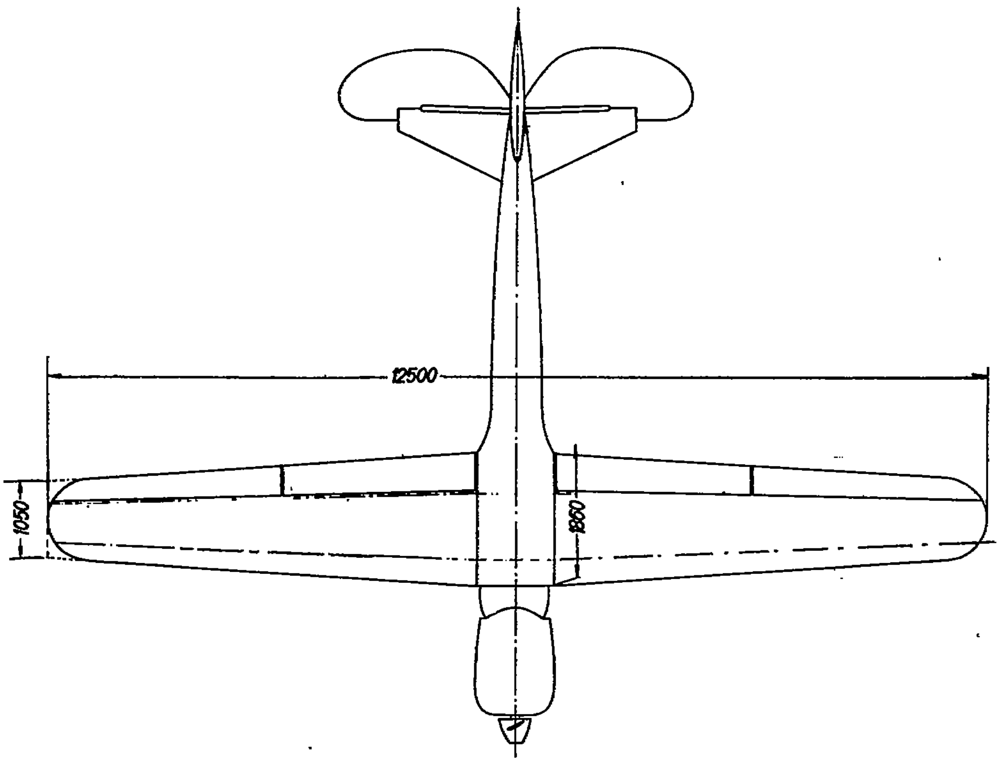


Figure 96.- Design of a second wing for the AF 2.

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